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REGIONAL CASE STUDY

# Incorporating coarse and fine recycled aggregates into concrete mixes: mechanical characterization and environmental impact

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## Abstract

Concrete waste (CW) recycling stands as a promising strategy to promote sustainable construction practices. This research aims to assess the feasibility of using recycled concrete aggregates (RCA) as a surrogate for natural aggregates (NA) in concrete applications and reduce the environmental impact associated with the depletion of natural resources and landfill space. To achieve these objectives, CW was segregated from debris mixes of construction and demolition waste (CDW), collected, crushed, and graded to generate RCA. Thirty-two concrete samples were prepared and categorized into four distinct groups with 0% (reference), 50%, 75%, and 100% substitution levels for both coarse RCA (CRCA) and fine RCA (FRCA), all utilized simultaneously. Concurrently, the environmental impacts of producing 1 $m^3$ of concrete were evaluated using a life cycle assessment (LCA) approach, (cradle-to-gate) covering three phases, the raw material supply (A1), transportation (A2) and concrete production (A3). At the 50% replacement level, the mechanical properties of recycled aggregate concrete (RAC) demonstrated a 20.0% increase in splitting tensile strength, accompanied by marginal decrease in workability (15.0%) and compressive strength (6.0%). In addition, at that percentage, the average environmental effects were reduced by 31.3%, with specific reductions of 34.7% for A1, 40.3% for A2, and no change in A3.

**Keywords** Concrete waste · Recycled concrete aggregates · Mechanical characterization · Environmental impacts

## Abbreviations

| | |
|---|---|
| CDW | Construction and demolition waste |
| CW | Concrete waste |
| RCA | Recycled concrete aggregates |
| CRCA | Coarse recycled concrete aggregates |
| FRCA | Fine recycled concrete aggregates |
| NA | Natural aggregates |
| CAN | Coarse natural aggregates |
| FNA | Fine natural aggregates |
| CC | Conventional concrete or traditional concrete |
| RAC | Recycled aggregate concrete |
| GHGs | Greenhouse gases |

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| | |
|---|---|
| LCA | Life cycle assessment |
| LCI | Life cycle Inventory |
| LCIA | Life cycle impact assessment |

## Introduction

The 2030 Agenda goals of United Nations (UN) aim to achieve reduction of 35% in greenhouse gases (GHGs) emissions, 42% in final energy consumption, and 50% in material extraction [1]. The construction sector exerts a significant influence on addressing key challenges, as it contributes to 40% of worldwide energy consumption [2], generate over 35% of GHGs [3], accounts for more than 50% of material extraction, utilizes about 30% of water resources, and it roughly contributes a third of waste production [4]. Within this context, construction and demolition waste (CDW) refers to the debris generated during the phases of constructing, renovating, and dismantling buildings, bridges, and other structures [5]. In developing countries, about 95% of produced CDW is disposed of on landfills or illegal dumping in unoccupied areas, along riverbanks, and onto roadways [6]. Nonetheless, an approximate 90% of CDW holds the capacity for reuse, recycling, or recovery [7]. CDW is a significant environmental challenge due to its considerable contribution to global waste generation as anticipated in Fig. 1 [8]. For example, China produced about 2.4 billion tons of CDW in total [9]. The European Union (EU) generated a collective amount of 850 million tonnes of CDW [10]. As one of the leading contributors to the global CDW, the United States generates an annual volume exceeding 600 million tons [11]. In Brazil, more than 45 million tons CDW is produced each year. Also, the current statistics indicate that the construction sector in Egypt generates an annual amount of 5.8 million tonnes of CDW [12], and the focus in this study on concrete waste.

Globally, concrete waste (CW) holds the majority share among the various types of CDW, constituting 85% in the USA, 81% in Australia, and 45% in China [14]. In Egypt, CDW primarily comprise dense materials such as concrete, bricks, sand, mortar, and tile remnants. Moreover, global

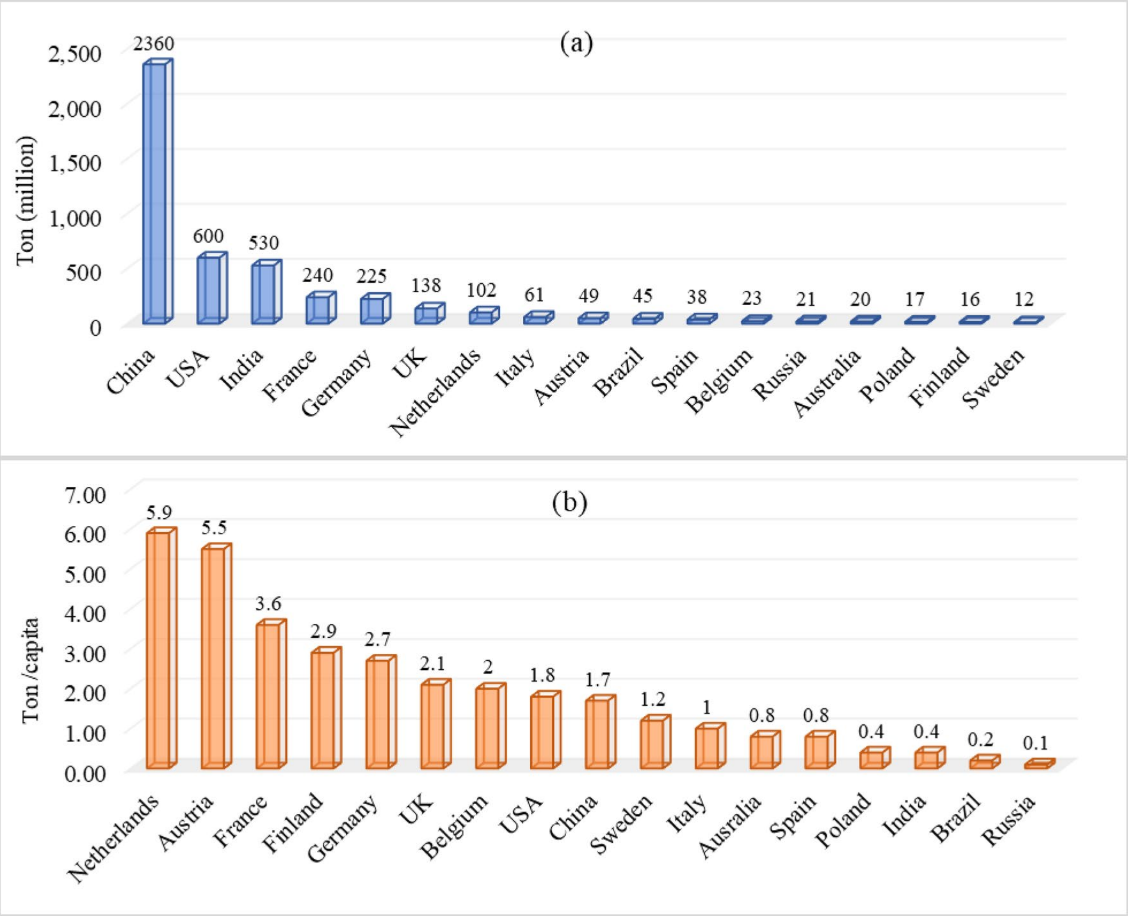


**Fig. 1** Countries with highest CDW generation: **a** CDW generation (million tons) and **b** CDW per capita (ton / capita) [13]

concrete consumption has soared from approximately 900 million tonnes in 1950 to nearly 30 billion tonnes in 2020 [15], driving the demand for 4.3 billion tons of cement and 19.4 billion tons of aggregate within the concrete sector [16]. Hence, the conversion of CW into a recycled concrete aggregate (RCA) represents a promising strategy [17]. In practice, RCA is generated by mechanically crushing discarded concrete into particles of aggregate size, encompassing both the constituents of crushed coarse RCA (CRCA) and fine RCA (FRCA) [18]. The studies indicate that treating one ton of CW can yield approximately 650 kg of CRCA, 330 kg of FRCA, and 20 kg of residual waste [19]. In relation to this study, there has been limited exploration into the simultaneous integration of varying proportions of CRCA and FRCA to develop “green concrete” or recycled aggregate concrete (RAC) [20].

In this context, the repurposing of CW involves recycling it into both CRCA and FRCA, which can then be employed in creating a blend referred to as RCA mixture [21]. The using of CRCA solely has been widely studied [22]. Contemporary standards and codes in environmentally progressive countries allow incorporating CRCA up to 30 weight percent (wt.%) for use in structural concrete applications [23]. A distinct investigation affirmed that the water absorption of CRCA surpasses that of coarse natural aggregate (CNA) by a range of 6.4% to 7.7% [20]. Conversely, there is a significant demand for utilizing FRCA in concrete with quality control needs in comparison to fine natural aggregate (FNA) [24]. FRCA is characterized by dimensions below 5 mm, originates from the crushing and sieving of fragments from aged concrete mortar [18]. Existing policies currently do not promote the inclusion of FRCA in cementitious blends, primarily due to the absence of consensus regarding its impact on mix performance [25]. This lack of endorsement for FRCA stands in contrast to the more prevalent acceptance of CRCA [26]. The water absorption capacity (WA), which serves as an indicator of FRCA porosity, remains a subject of unresolved debate. The literature presents a broad spectrum of WA values, ranging from 2.4% to 19.3% [20, 27–30].

In addition, the behaviour of RAC incorporating high volumes of both FRCA and CRCA presents certain complexities that require further investigation. It has been observed that as the replacement of NA with RCA increases, the workability of the concrete diminishes, leading to a more pronounced reduction in slump compared to conventional concrete (CC) [31]. In contrast, some researchers suggest replacing 30% of CRCA and 20% of FRCA yield comparable compressive strength as CC [32]. An alternative study determined that a viable approach involves restricting usage to a simultaneous blend of up to 60% CRCA and 30% of FRCA, coupled with a water-to-cement (W/C) ratio of 0.48, while maintaining suitable properties [33]. In instances, where both CRCA and FRCA are utilized at a replacement rate of 100%, there is a notable decrease in cube compressive strength, ranging from 36 to 42% [34]. However, Pedro et al. have noted that concrete incorporating both coarse and fine RCAs simultaneously can achieve comparable performance to CC [35]. As an example, the compressive strength experiences a relatively modest decrease (approximately 10%) when the replacement ratios reach 30% of coarse aggregate and 20% for fine aggregate. In addition, tensile strength witnesses a reduction of 5% to 15% when replacing 50% of coarse aggregate, and up to 35% when substituting 50% of fine aggregate [36, 37]. Plaza et al. conducted a study revealing that the simultaneous utilization of both fine (50%) and coarse (100%) of RCA led to diminished strength compared to the CC. This approach incurred strength reductions of up to 14.13% [43].

Beside the above mentioned mechanical characteristics, the environmental merits of recycling CW, is a way of transition to green the concrete industry, avoid landfills, reduce consumption of natural materials [38]. The implementation of life cycle assessment (LCA) has gained extensive traction in the ecological consequences of waste handling strategies [39]. LCA is utilized to assess both the energy and environmental impacts of products or services [40]. It provides valuable understanding into the environmental aspects linked with the adoption of technologies and strategies in the management of CW [41]. For instance, it can be argued that the complete substitution of crushed granite with recycled coarse aggregate could potentially result in 7% reduction in GHGs [42]. In a study carried out in Hong Kong demonstrated that incorporating various recycled materials, such as reclaimed stone aggregates, bricks, and concrete blocks

**Table 1** Concrete mixtures with different proportions of recycled aggregate

| Mixes | %RCA | Cement (kg) | W/C | CNA (kg) | FNA (kg) | CRCA (kg) | FRCA (kg) |
|---|---|---|---|---|---|---|---|
| Mix (1) [Conventional mix] | 0% | 300 | 0.425 | 1347.25 | 673.6 | 0 | 0 |
| Mix (2) | 50% | 300 | 0.425 | 673.6 | 336.8 | 673.6 | 336.8 |
| Mix (3) | 75% | 300 | 0.425 | 336.8 | 168.41 | 1010.44 | 505.2 |
| Mix (4) | 100% | 300 | 0.425 | 0 | 0 | 1347.25 | 673.6 |

**Table 2** Concrete mix design information for grade 25 concrete

| Component | Value |
|---|---|
| Design strength | 25 MPa at 28 days |
| Standard deviation | 3.0 MPa (very good control) ACI |
| Margin | 1.64 * 3.0 = 4.92 MPa |
| Target mean strength | 25 + 4.92 = 29.92 MPa |
| Free water / cement ratio | 0.425 |

in the construction of concrete buildings led to GHGs reductions ranging from 6 to 17% [43].

The knowledge gaps and motivation revolve around the feasibility of incorporating significant amounts of both FRCA and CRCA into RAC. The simultaneous use of CRCA and FRCA can offer performance levels comparable to CC, particularly with careful selection of replacement ratios for aggregates. Furthermore, the adoption of such practices can yield substantial environmental benefits, specifically when considering LCA for recycling scenarios in contrast to traditional concrete production methods.

The objective of this research is to measure the mechanical characteristics and the associated environmental impacts for RAC made with substitution of CRCA and FRCA in concrete applications. Four concrete mixtures, 0% (reference or CC), 50%, 75%, and 100% RCA replacement, were prepared with fixed W/C ratio for all mixes. On the other hand, a LCA (cradle-to-gate) was applied for all mixtures. As a result, a comparative LCA evaluation framework is constructed. This framework is initiated using a practical real construction project, which is anticipated to have considerable environmental merits.

This work is organized into four sections. This section for introduction and literature review on the RCA derived from CDW. Additionally, it provides an overview of the methodology of LCA in the context of the CDW sector. "Materials and methods" section outlines the research methodology employed to accomplish the objectives of this study. The findings of the research are presented in "Results and discussion" section, where RCA are categorized based on the mechanical characteristics and cradle-to-gate LCA during the stages of concrete waste recycling activities. Finally, the paper concludes by highlighting the study's contributions and key findings.

## Materials and methods

### Materials and reagents

The application of recycled concrete aggregates (RCA) serves as a widely embraced method on behalf of repurposing concrete waste, aligning well with the principles of sustainable development [44]. The primary objective of the experimental program is to assess the feasibility of substituting coarse and fine natural aggregates (CNA and FNA) with recycled concrete aggregate (CRCA and FRCA) as a solution to address raw materials scarcity and land utilization concerns, while promoting the adoption of recycled materials. The incorporation of RCA offers a potential remedy for the challenges posed by remote areas of NA sources, which can incur higher transportation emissions.

To achieve this goal, a laboratory investigation program was conducted to explore the viability of incorporating RCA in concrete mixes, replacing NA at varying proportions (50%, 75%, and 100%). The physical attributes of both RCA and NA were analysed, encompassing specific gravity, water absorption, bulk density, particle size distribution

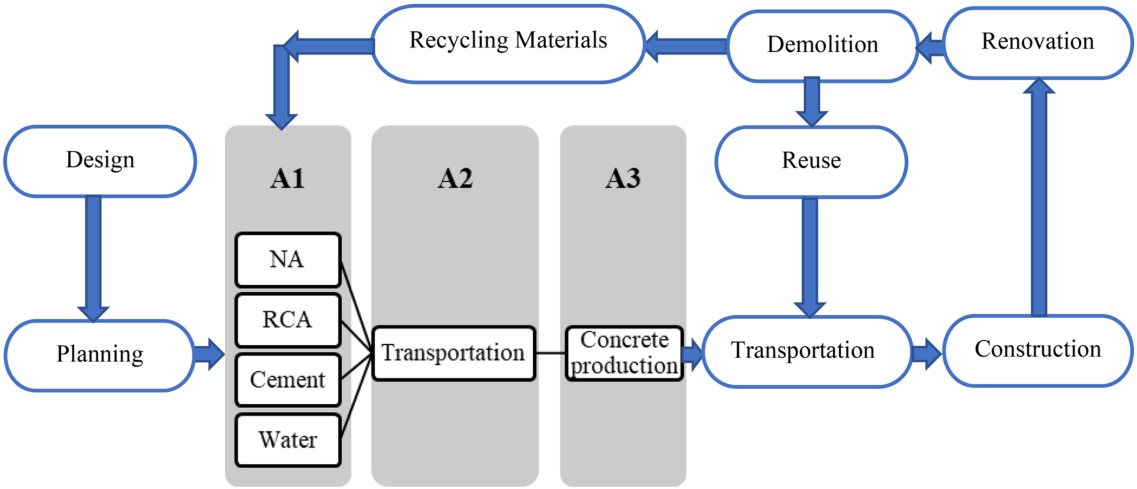


**Fig. 2** Life cycle including system boundary (A1–A3)

**Table 3** Impact categories considered in the LCA

| Impact category | Unit |
|---|---|
| Climate change | kg $CO_2$ Eq |
| Ozone depletion | kg CFC11 Eq |
| Ionising radiation | Kbq U-235 Eq |
| Photochemical ozone formation | Kg NMVOC Eq |
| Acidification | Mol H + Eq |
| Eutrophication, freshwater | kg P Eq |
| Eutrophication, marine | kg N Eq |
| Land use | Pt |
| Resource use, fossils | Mj |

(PSD), fineness modulus (for fine aggregate), and clay and silt content (for fine aggregate). The subsequent phase focussed on evaluating the workability of the fresh concrete as per the European Standard EN 12350-2 [45]. Ultimately, the compressive strength of 16 cubic specimens measuring 15 × 15 × 15 cm was tested in accordance with ASTM C39 (American Society for Testing and Materials) standards. Additionally, the split tensile strength was determined using 16 cylindrical samples measuring 15 × 30 cm, following the guidelines outlined in ASTM C496/C496M [46]. To ensure precision and dependability, each mixture underwent two rounds of testing.

## Materials

In this study, coarse aggregates with a grade of 4.75–50 mm were used, including gravel round, and crushed as coarse NA and crushed concrete rubble as coarse RCA. Two types of fine aggregates were used: fine NA from gravel and sand quarry and fine RCA, which were crushed concrete debris passing through a 4.75 mm sieve. The RCA materials were acquired from leading landfill sites in New Aswan City (Egypt), including demolished structures, and manually crushed. The aggregates underwent testing as per the ASTM C136/C136M [47]. In relation to cement, CEM I 42.5N was employed, and the assessment of cement was conducted following the guidelines outlined in the Egyptian Standard Specifications ESS 2421/2007 [48]. The selected cement adhered to the specifications set forth in ESS 4756-1/2009 [49]. Notably, the choice of cement type emerged as a pivotal factor, wherein CEM II/B and CEM V cements exhibited more pronounced capability in minimizing global warming potential (GWP) as opposed to CEM I cement [50].

**Table 4** physical properties of the coarse and fine aggregates

| Property | Coarse aggregates | | Fine aggregates | | Standard test |
|---|---|---|---|---|---|
| | CNA | CRCA | NFA | FRCA | |
| Specific gravity | 2.74 | 2.19 | 2.68 | 1.70 | ASTM 127/128 |
| Water absorption (%) | 1.34 | 9.10 | 2.35 | 16.95 | ASTM 127/128 |
| Bulk density (kg/$m^3$) | 1650 | 1220 | 1600 | 1300 | ASTM29 |
| Fineness modulus | 2.55 | 3.45 | – | – | ASTM125 |
| Clay and silt content (%) | 3.50 | 3.70 | – | – | ASTM142 |

**Fig. 3** The case study, including landfill, recycling plant, and ready-mix plant data

### Concrete mix design and testing methods

The concrete mixture design was formulated following the guidelines outlined in the American Concrete Institute (ACI) 211.1 standard [51]. The mix proportion of the concrete compositions were determined using the absolute volume method [52]. RCA is used to refer to both coarse and fine RCA. Similarly, NA will be used to represent both coarse and fine NA. The specimens were subjected to testing at both 7 days and 28 days of age in accordance with the Egyptian Code for Design and Construction of Concrete Structures (ECP 203-2018) as it is the standard curing time by immersion using potable water [53]. Four concrete mixes, as depicted in Tables 1 and 2, have been formulated for a total of thirty-two samples. The objective is to compare the properties of concrete produced using solely NA and varying percentages of RCA. Mix 1, consisting of NA alone, serves as the reference mix. The other three mixes (Mixes 2, 3, and 4) incorporate RCA replacements of 50%, 75% and 100%, respectively. All mixes maintain a fixed ratio of coarse to fine aggregate with (2:1) in sequential order. In addition, a uniform cement content of 300 kg/m$^3$ is maintained across all blends.

## Environmental program

### Comparative LCA: goals, boundary, and impact assessment

Improper management of CDW poses numerous detrimental effects, such as global warming, ozone layer depletion, aquatic eutrophication, etc. [54]. This study aligns with the framework of LCA as outlined in ISO 14040:2006 [55] and ISO14044:2006 [56], and it also adheres to EN 15804 [57]. The research encompasses four fundamental steps: (1) defining the goal and scope, (2) conducting an inventory analysis, (3) performing an impact assessment, and (4) interpreting the results [58]. The primary aim of this LCA is to evaluate the environmental advantages of substituting NA with RCA derived from concrete waste in RAC production. A cradle-to-gate LCA comparison was conducted between the "reference" concrete (Mix1) and concrete mixes with varying levels of NA replacement by RCA, specifically 50% (Mix2), 75% (Mix3), and 100% (Mix4). The system boundary depicted in Fig. 2, designated as "cradle-to-gate." This boundary covers life cycle stages including the target boundary as follow: raw material supply (A1), transportation to the concrete plant (A2), and the manufacturing of ready-mix concrete (A3) [59].

The Ecoinvent 3.8 database and SimaPro 9.4.0.2 are extensively utilized tools for conducting environmental impact assessments. The Ecoinvent 3.8 database is a robust and all-encompassing resource that provides LCI data for

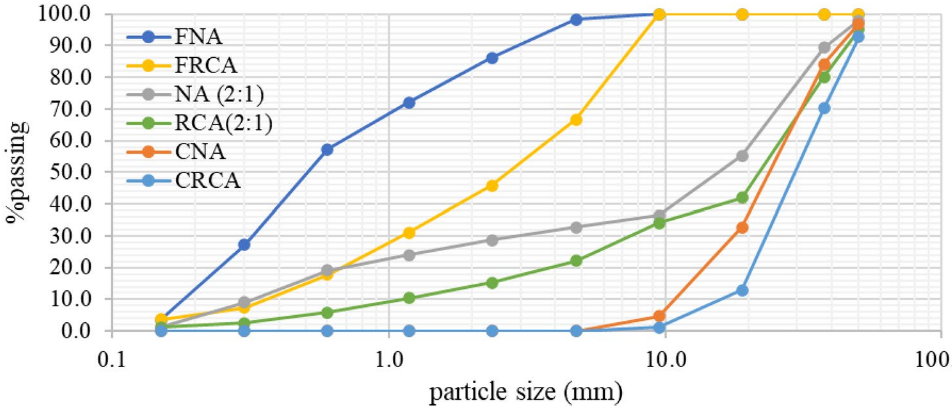


**Fig. 4** Particle size distribution (PSD)

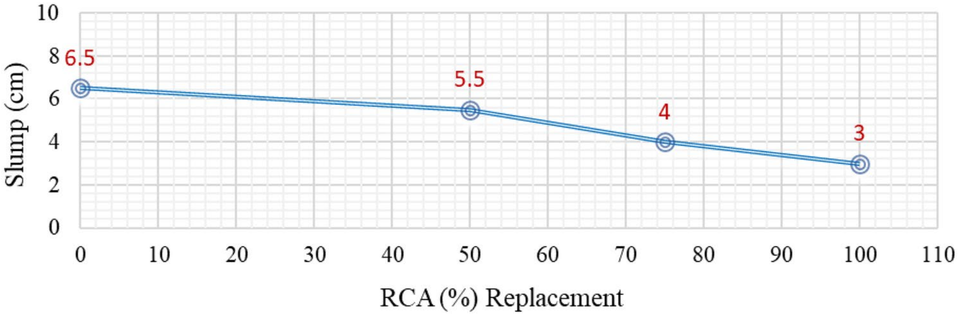


**Fig. 5** Slump value of the recycled concrete mixes versus the percentage of RCA

**Fig. 6** Curing of samples and compressive strength and indirect tensile strength tests

**Table 5** Average compressive strength and splitting tensile strength of the concrete

| RCA % | Compressive strength at 7 days (MPa) | | Compressive strength at 28 days (MPa) | | Splitting tensile strength at 7 days (MPa) | | Splitting tensile strength at 28 days (MPa) | |
|---|---|---|---|---|---|---|---|---|
| | Average | Standard deviation | Average | Standard deviation | Average | Standard deviation | Average | Standard deviation |
| 0% RCA | 19.1 | 0.5 | 28.7 | 0.8 | 1.2 | 0.1 | 1.7 | 0.1 |
| 50% RCA | 18.0 | 0.8 | 27.0 | 1.1 | 1.5 | 0.1 | 2.2 | 0.1 |
| 75% RCA | 12.2 | 3.3 | 18.3 | 5.0 | 1.4 | 0.1 | 2.1 | 0.1 |
| 100% RCA | 6.2 | 0.4 | 9.3 | 0.6 | 0.6 | 0.1 | 0.9 | 0.2 |

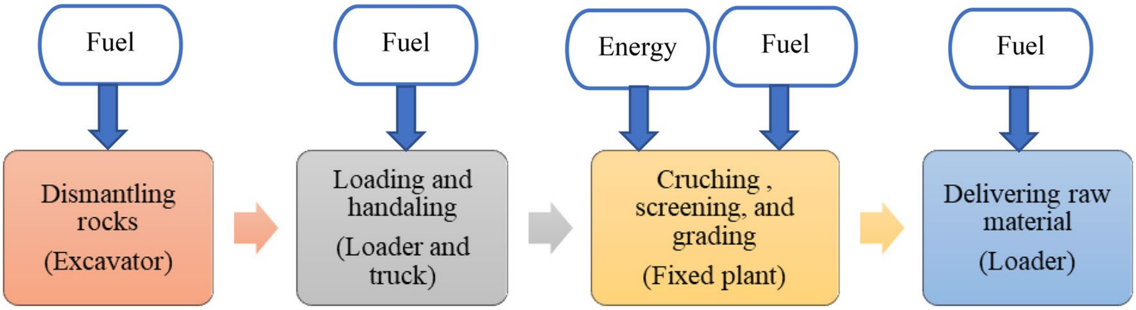


**Fig. 7** Production Process of NA (CNA + FNA)

diverse products and processes. It enables the evaluation of environmental impacts across different phases of lifecycle, encompassing raw material extraction, manufacturing, transportation, utilization, and disposal [60]. The integration of SimaPro 9.4.0.2 with the Ecoinvent 3.8 database enables users to conveniently access data and conduct LCA analyses. This integration provides users with the capability to evaluate the environmental effects linked to diverse products and processes [61]. The EN 15804 + A2 Method is utilized for assessing the impact categories as outlined in Table 3. These parameters provide a comprehensive description of the environmental effects based on the established standards [62].

### Functional unit (FU)

This study employs a functional unit (FU) of 1 m3 of concrete, as recommended by various studies [63]. The assessment encompasses inputs related to resources, production, energy consumption, and transportation, while also considering outputs, such as waste generated from material processing, emissions, and machine utilization. In order to facilitate accurate comparisons for this FU, the research focuses on concrete mixtures with comparable basic mechanical properties and similar functional requirements.

### Case study: new Aswan city

The case study (New Aswan City), as shown in Fig. 3, is located in Upper Egypt at coordinates 24.085°N 32.904°E

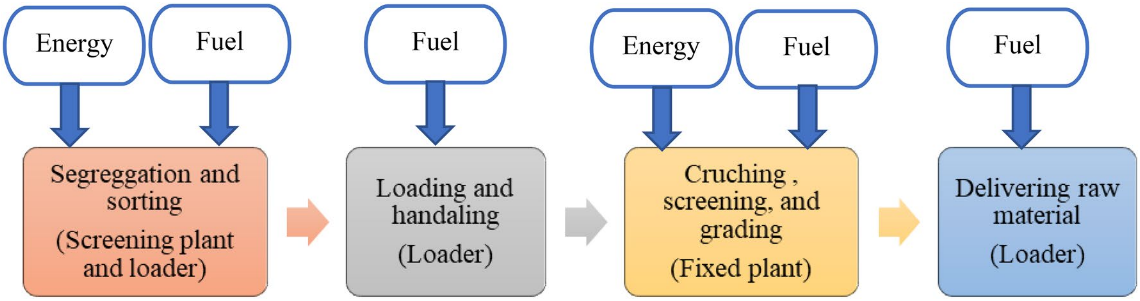


**Fig. 8** Production Process of RCA (CRCA + FRCA)

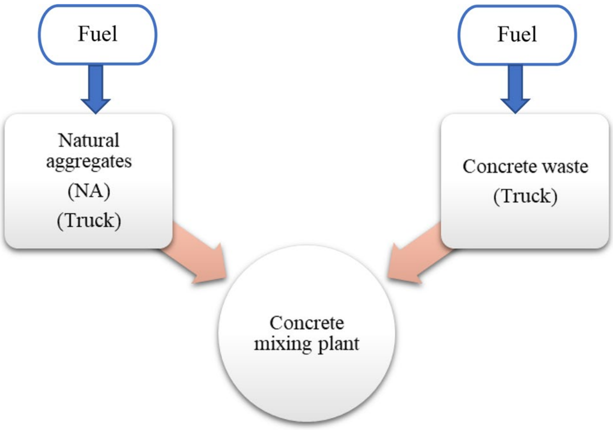


**Fig. 9** Transportation Phase

and it was built starting in 1999 as part of the Egyptian government plan to develop housing in desert regions as a means of curbing urban sprawl encroaching upon agriculture lands. It is situated 12 km north of Aswan and across the Nile river [64].

## Results and discussion

### Mechanical characterization results

#### Physical properties of NA and RCA

The Utilization of RCA in concrete manufacturing significantly influences both concrete design approach and its properties. This is primarily due to the presence of impurities, as well as residual cement and mortar adhering to the RCA. These factors notably affect the chemical composition of the RCA, resulting in changes in properties like density, specific gravity, and absorption [65] as listed in Table 4. RCA typically exhibit a rough texture, primarily because of the presence of hardened cement and mortar, and an angular shape, which results from the crushing process [66]. Furthermore, the measurements of the characteristics were compared with the limits according to the ASTM specifications.

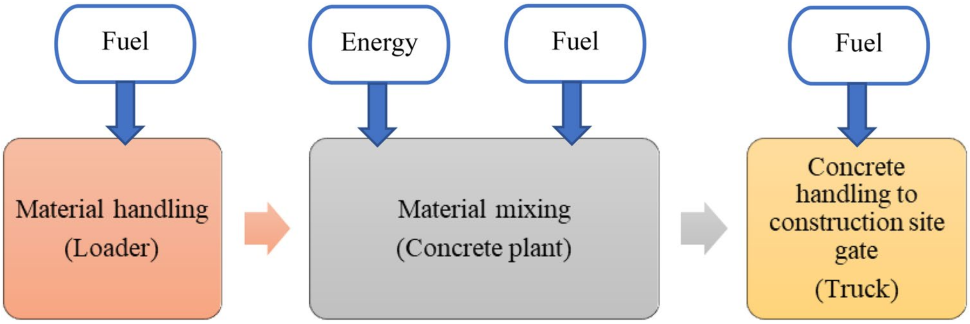
Generally, in comparison to conventional aggregates, the CRCA had a higher absorption rate and a lower specific gravity. The CNA absorbed between 0.2 and 4% of its weight [67]. In addition, according to the ASTM C128, most CNA have specific gravities between 2.40 and 2.90 [68]. Furthermore, based on ASTM C29, the gauge of the bulk density of the coarse aggregate fluctuates between 1200 kg/m$^3$ and 1750 kg/m$^3$ [69].

Absorption levels of the FNA ranges from 0.2% to 3% [70]. Meanwhile, FNA had a specific gravity between 2.40 and 2.90 according to ASTM C127 and ASTM C128. In this study, the relative density for the FNA was 2.68; while the FRCA showed a relative density of 1.70, which is under the minimum limit. Also, according to the ASTM C29, the range of the bulk density of the fine aggregate fluctuates between 1200 kg/m$^3$ and 1750 kg/m$^3$ [69]. The fineness modulus (FM) ranges between 2.3 and 3.1 as per the ASTM C125. The limits of the percent of the clay and silt according to ASTM C142 must not exceed 5% of the amount passing from sieve (NO. 200) [71]. The particle size distribution (PSD) of the aggregates was carried out by the sieve analysis test, executed in accordance with ASTM C136 [72]. The PSD curves are shown in Fig. 4, the limits of the grading situated within the recommended specifications, which is acceptable for manufacturing concrete according to ASTM C33 [73]. The maximum particle size is 50 mm, which satisfies the quality requirements.

#### Fresh properties of RAC (workability)

Concrete workability is an indicator of its ease in preparation, application, compaction, and finishing, all while maintaining its homogeneity without significant disruptions [74]. The slump test was carried out based on the ASTM C143, which summarizes the normal concrete having a slump

**Fig. 10** Manufacturing Phase



within a range 50 mm to 75 mm [75]. Figure 5 shows the values of the slump, which considered acceptable for the control mix (Mix 1) and Mix 2 with 50% of RCA. Moreover, the results were found under the limits for Mixes 3 and 4 containing an RCA amount equal to 75% and 100%, respectively. The main factors that affected the values of the slump in this study were the shape of aggregates and their surface texture. The more the RCA, the more decrease of the workability or the slump value will be.

### Hardened RAC properties (compressive and splitting tensile strengths)

The compressive tests were carried out according to ASTM C39, Fig. 6, at 7 and 28 days [76]. The average values of the two replicates for each mix, when crushed under compressive axial load are presented in Table 5. The results showed that the values of compressive strength are almost equal for mixes with no RCA and 50% RCA replacement. On the other hand, for replacements equal and higher than 75%, the average compressive strength was much lower and did not exceed 18.3 and 9.3 MPa after 28 days for mix 3 and Mix 4, respectively. As such, the usage of very high quantity of RCA will be limited for non-structural applications only.

The indirect tensile strength of concrete is typically accounts for approximately 8% to 12% of the compressive strength [77]. Hossein and Farhad [78] discovered that the replacement of NA with RCA could potentially lead to either an increase or decrease in tensile strength. According to ASTM C496 [79], Table 5 provides the tensile values, which represent the mean results from two replicates for each mixture, obtained through testing under indirect axial loading conditions. The results of indirect tensile strength showed that an increase in the strength for RCA mixes for replacement levels up to 75%, while a sharp decrease was registered for the total replacement of NA with RCA.

## Life cycle assessment (LCA) of RAC: assumptions and results analysis

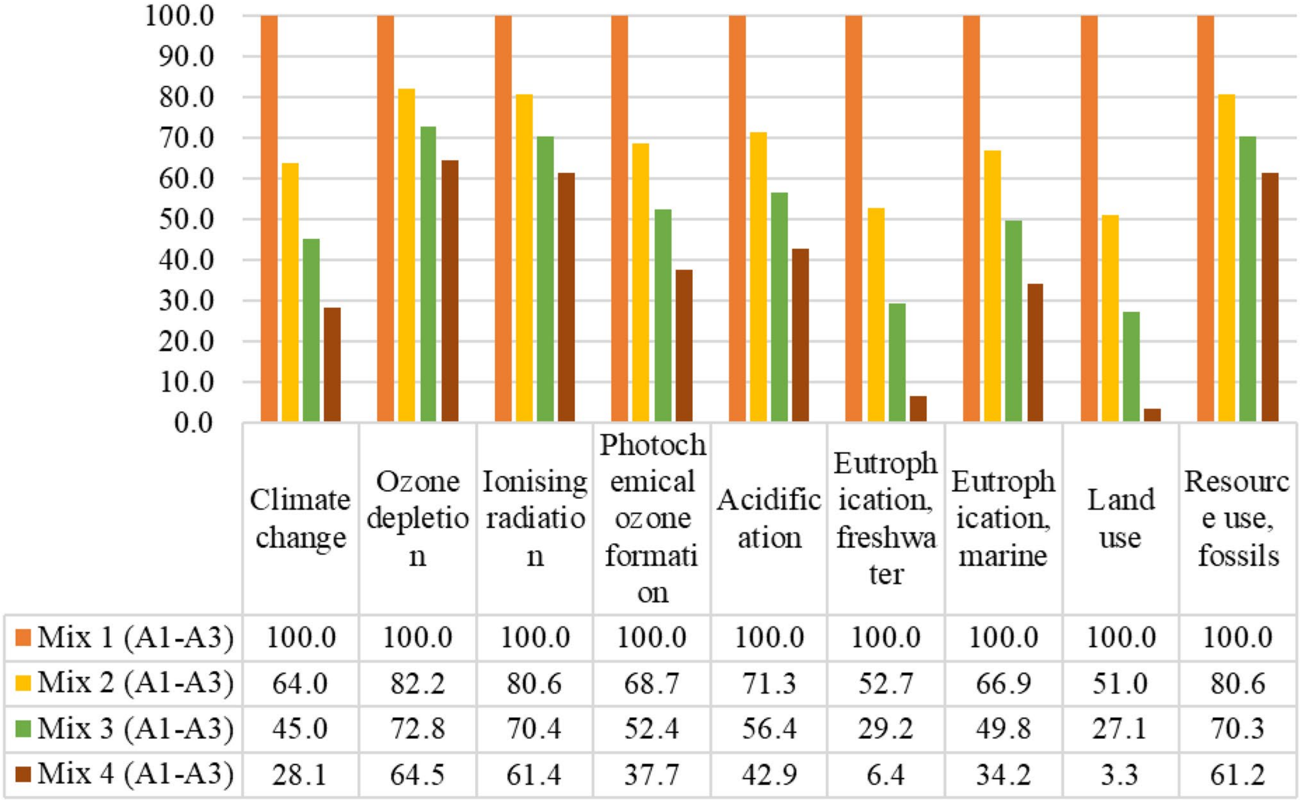
### System boundaries

To ensure the viability of this study, several key assumptions have been made. Firstly, the potential effects stemming from the internal transportation of waste within the CDW recycling facility have been excluded from consideration [80]. Additionally, the study assumes that both the recycling plant and the ready-mix concrete plant are constructed at the boarder of the landfill position, as depicted in Fig. 3. Furthermore, the recycling plant comprises a screening plant and a fixed crusher plant for RCA production, with the output assumed to consist of a 2:1 ratio of coarse to fine RCA.

In terms of transportation, the average distance from the source of CDW to the landfill has been assumed 5.0 km as illustrated in Fig. 3. Moreover, certain emissions arising from various stages of raw material production or extraction,

**Table 6** Life cycle impact assessment – A1 to A3 phases

| Impact category | Unit | Mix 1 | Mix 2 | Mix 3 | Mix 4 |
|---|---|---|---|---|---|
| Climate change | kg $CO_2$ eq | 45.9 | 29.4 | 20.7 | 12.9 |
| Ozone depletion | kg CFC11 eq | 1.7E-05 | 1.4E-05 | 1.3E-05 | 1.1E-05 |
| Ionising radiation | kBq U-235 eq | 4.7 | 3.8 | 3.3 | 2.9 |
| Photochemical ozone formation | kg NMVOC eq | 2.0E-01 | 1.4E-01 | 1.0E-01 | 7.4E-02 |
| Acidification | mol H + eq | 2.3E-01 | 1.6E-01 | 1.3E-01 | 9.8E-02 |
| Eutrophication, freshwater | kg P eq | 3.1E-04 | 1.6E-04 | 9.1E-05 | 2.0E-05 |
| Eutrophication, marine | kg N eq | 6.2E-02 | 4.1E-02 | 3.1E-02 | 2.1E-02 |
| Land use | Pt | 64.2 | 32.8 | 17.4 | 2.1 |
| Resource use, fossils | MJ | 1097.2 | 883.9 | 771.5 | 671.8 |



| | Climate change | Ozone depletion | Ionising radiation | Photochemical ozone formation | Acidification | Eutrophication, freshwater | Eutrophication, marine | Land use | Resource use, fossils |
|---|---|---|---|---|---|---|---|---|---|
| 🟧 Mix 1 (A1-A3) | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 🟨 Mix 2 (A1-A3) | 64.0 | 82.2 | 80.6 | 68.7 | 71.3 | 52.7 | 66.9 | 51.0 | 80.6 |
| 🟩 Mix 3 (A1-A3) | 45.0 | 72.8 | 70.4 | 52.4 | 56.4 | 29.2 | 49.8 | 27.1 | 70.3 |
| 🟫 Mix 4 (A1-A3) | 28.1 | 64.5 | 61.4 | 37.7 | 42.9 | 6.4 | 34.2 | 3.3 | 61.2 |

**Fig. 11** Weighting the total environmental impacts of 1 m$^3$ concrete production (cradle to gate)

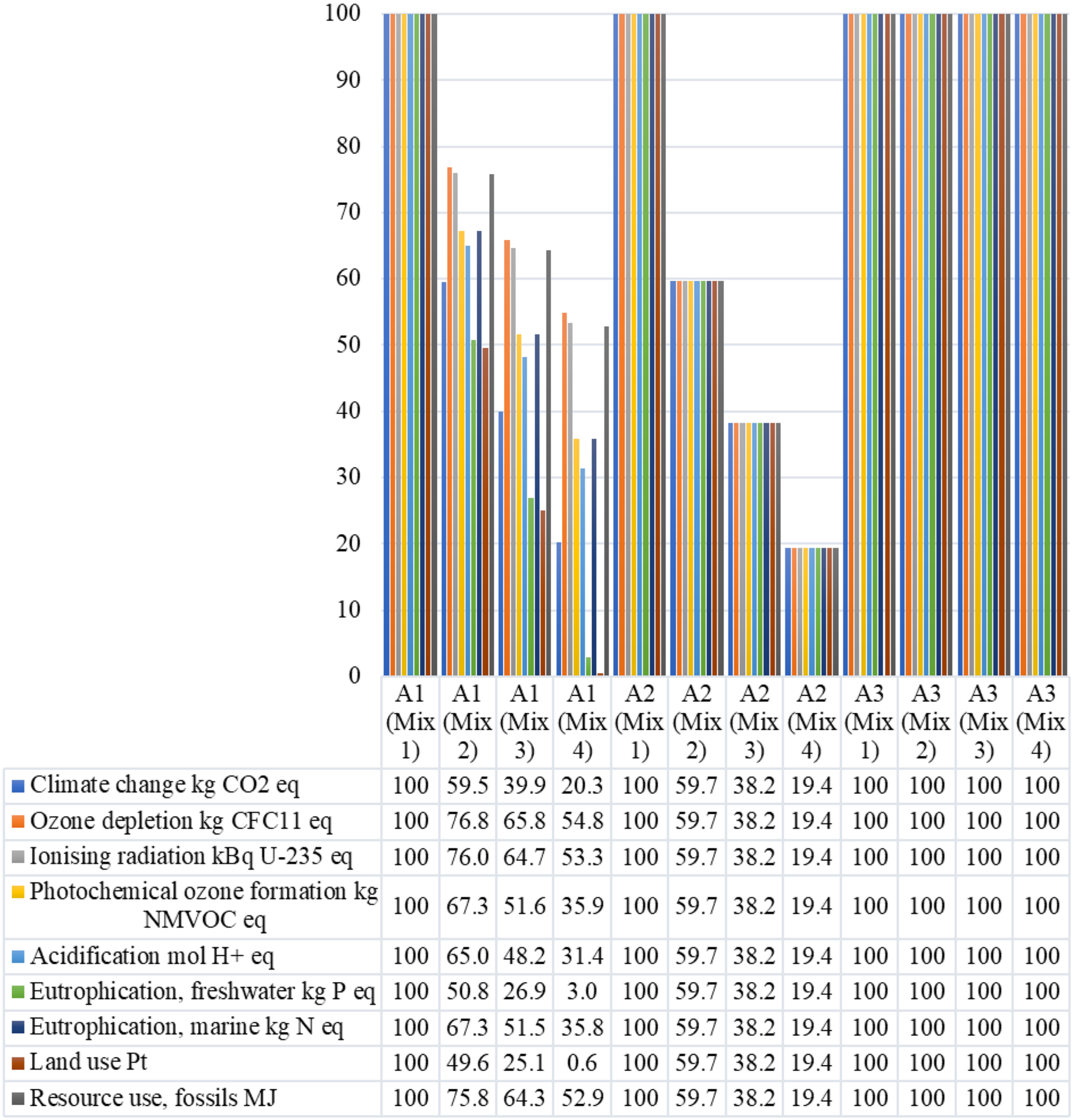
such as diffuse dust emissions at quarry sites and CW recycling plants, have not been included in the assessment due to limited available information. However, it is important to note that these emissions are typically considered insignificant, thereby negating the need for a sensitivity analysis on this matter [80].

For concrete production, it is assumed that the water source is a direct pipeline from the city water supply system, eliminating the need to estimate water-related environmental impacts. Furthermore, the source of CDW processes such as deconstruction and truckload are not considered. Since the quantity of cement remains constant across all mixtures, the estimation of cement production and transportation impacts have been excluded from assessment.

### Life cycle inventory (LCI)

The data collection process relied on reviewing pertinent literature and extracting information from the Ecoinvent 3 Life Cycle Inventory (LCI) database. The primary data collected, and the underlying assumptions can be summarized as follows; The eco-profile for NA is represented by the entry "Gravel, round." [81] in the Ecoinvent 3 database production. Additionally, "Sand" is utilized as references for the eco-profiles associated with gravel and sand quarry operations in the database [81]. With regard to RCA, the fuel and electricity consumption of fixed plants in their production is estimated to be 1.74 kWh per ton of recycled concrete aggregates. Furthermore, for every 1 ton of supplementary raw material produced, approximately 0.38 Litres of diesel is consumed. The production of one ton of RCA from a fixed plant requires the use of 0.03 kg of steel [82]. In terms of transportation, the assumptions were made that the materials are transported via road. Therefore, the impact associated with the transportation per ton-kilometre was evaluated using the reference item "Transport, freight, lorry 16–32 metric tonne, EURO5 market for Alloc Def, S" in the Ecoinvent 3 database. The travelling distance was obtained through the utilization of Geographic Information System (GIS) mapping; the distance from natural aggregate quarry to ready-mix plant is 100.0 km.

Furthermore, in the cement concrete manufacturing phase, the electricity consumption for mixing one m$^3$ of concrete is estimated to be 2 kWh. Additionally, the diesel fuel consumption is approximately 12.65 L, considering a diesel density of 0.84 kg/L, which includes the mixing



| | A1 (Mix 1) | A1 (Mix 2) | A1 (Mix 3) | A1 (Mix 4) | A2 (Mix 1) | A2 (Mix 2) | A2 (Mix 3) | A2 (Mix 4) | A3 (Mix 1) | A3 (Mix 2) | A3 (Mix 3) | A3 (Mix 4) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ■ Climate change kg CO2 eq | 100 | 59.5 | 39.9 | 20.3 | 100 | 59.7 | 38.2 | 19.4 | 100 | 100 | 100 | 100 |
| ■ Ozone depletion kg CFC11 eq | 100 | 76.8 | 65.8 | 54.8 | 100 | 59.7 | 38.2 | 19.4 | 100 | 100 | 100 | 100 |
| ■ Ionising radiation kBq U-235 eq | 100 | 76.0 | 64.7 | 53.3 | 100 | 59.7 | 38.2 | 19.4 | 100 | 100 | 100 | 100 |
| ■ Photochemical ozone formation kg NMVOC eq | 100 | 67.3 | 51.6 | 35.9 | 100 | 59.7 | 38.2 | 19.4 | 100 | 100 | 100 | 100 |
| ■ Acidification mol H+ eq | 100 | 65.0 | 48.2 | 31.4 | 100 | 59.7 | 38.2 | 19.4 | 100 | 100 | 100 | 100 |
| ■ Eutrophication, freshwater kg P eq | 100 | 50.8 | 26.9 | 3.0 | 100 | 59.7 | 38.2 | 19.4 | 100 | 100 | 100 | 100 |
| ■ Eutrophication, marine kg N eq | 100 | 67.3 | 51.5 | 35.8 | 100 | 59.7 | 38.2 | 19.4 | 100 | 100 | 100 | 100 |
| ■ Land use Pt | 100 | 49.6 | 25.1 | 0.6 | 100 | 59.7 | 38.2 | 19.4 | 100 | 100 | 100 | 100 |
| ■ Resource use, fossils MJ | 100 | 75.8 | 64.3 | 52.9 | 100 | 59.7 | 38.2 | 19.4 | 100 | 100 | 100 | 100 |

**Fig. 12** Weighting the environmental effects for each phase (A1, A2, and A3) of 1 m$^3$ concrete production for "Mix 2", "Mix 3", and "Mix 3" in regard to "Mix 1"

process. The presumption is made regarding the distance required for transporting extracted materials within the concrete plant is 10 km, and the distance from the mixing plant to the construction site gate is also 10 km [83]. These data constituted the LCI are shown in Figs. 7, 8, 9, and 10, they were modelled according to the characterization factors listed in EN 15804:2019 + A2 method for life Cycle Impact Assessment (LCIA).

### Life cycle impact assessment (LCIA)

LCIA is employed to elucidate the magnitude of the environmental effects associated with the results obtained in a

LCI [84]. The LCIA results for A1 to A3 phases are listed in Table 6. The environmental impacts of the four mixes were evaluated using the EN 15804:2019 + A2 method standard for each category. Moreover, the bar graph Fig. 11 shows the percentage of environmental burdens comparison through each mix.

The main observations from this study indicate significant reductions in environmental impacts when comparing different concrete mixes to a reference mix (Mix 1). Mix 2, Mix 3, and Mix 4, demonstrated average reductions of 31.3%, 47.4%, and 62.3% in environmental impacts, respectively. Notably, the impact category of land use was the most affected by the replacement of NA with RCA, with reduction values of 49.0%, 72.9%, and 96.7% for Mix 2, Mix 3, and Mix 4, respectively.

Specifically, when considering climate change impact per cubic metre, Mix 2, which featured a 50% RCA replacement, exhibited a remarkable 36.0% reduction compared to conventional concrete. These findings align with a prior study that indicated substituting NA with excavated soil and RCA can reduce total energy consumption by 5% within a cradle-to-gate boundary [85].

However, it is worth noting that not all studies have found such significant improvements in environmental impact categories when incorporating RCA into concrete production. For instance, another study focussing on cradle-to-gate (LCA) of concrete block production with RCA did not reveal significant improvements in most of the impact categories [58]. These results highlight the variable environmental outcomes associated with the use of RCA in concrete production, underscoring the importance of careful consideration and context-specific analysis in sustainable construction practices.

On the other hand, Fig. 12 provides insights into GHGs categorized as A1, A2, and A3 for each concrete mix. The study reveals varying environmental reductions during the raw material phase (A1), a consistent decline in emissions during the transportation phase (A2), and stable values in the concrete manufacturing phase (A3).

Specifically, Mix 2, when compared to the reference mix (Mix 1), demonstrates reductions of 34.7% in A1, 40.3% in A2, and no change in A3. Notably, the primary driver of environmental performance improvement stems from transportation savings (A2) associated with RCA. Consequently, when considering Mix 1 as baseline, reductions of 40.3%, 61.8%, and 80.6% were achieved for Mix 2, Mix 3, and Mix 4, respectively.

Regarding the extraction phase (A1), the most substantial reductions for Mix 2, Mix 3, and Mix 4, in comparison to Mix 1 or conventional concrete, are observed in the land use and eutrophication impact categories. These reductions are quantified as 49.6%, 25.1%, 0.6%, and 50.8%, 26.9%, and 3.0%, respectively. These findings corroborate previous studies highlighting the significant influence of transportation distance on the environmental benefits of using recycled aggregates [86].

In summary, the quantitative environmental performance measurements presented in this study provide a valuable foundation for evaluating different equivalent proposals during decision-making processes related to sustainable construction materials.

## Conclusions and future work

The results fulfilled in that research lead to the following conclusions:

- CW might be recycled into useable aggregates for use in concrete manufacturing, with qualities suitable for most concrete purposes.
- The PSD for the CNA and CRCA were close to each other.
- The slump values of the fresh concrete up to 50% RCA replacement were within the standard limits for the international codes.
- The recycled concrete with substitution ratio up to 50% RCA by the total NA and 300 kg/m3 cement content produced concrete up to 27 MPa compressive strength, which is feasible for most concrete applications. Moreover, the recycled concrete with 50% of RCA met the related specifications and it can represent a more sustainable solution.
- Interestingly, the indirect tensile strength of the RCA mix is higher than that of the NA mix up to 75% replacement of RCA. This indicates the positive side of using RCA in concrete mix for different applications.
- The environmental impact reduction of using RCA as a substitution for the NA, leads to more attention to the importance of recycling.
- Transportation considers the main factor affected by GHG emissions decreasing based on traditional mix (Mix 1) with values of 40.30%, 61.80%, and 80.60% for Mix 2, Mix 3, and Mix 4, respectively.
- Using a consistent and standardized methodology, the study can provide a valuable tool for decision-making when it comes to sustainable construction practices and the use of RCA in concrete production.

Based on the aforementioned findings, it is feasible to substitute 50% of NA with RCA in concrete applications. Additionally, to achieve environmental advantages, it is advised that regulatory bodies encourage demolition contractors to establish crushing and screening facilities for utilizing CW in concrete mixes.

The future scope of work should focus on further research and exploration of the transition towards a circular economy in the CW sector. This entails investigating methods to optimize waste management and resource utilization, emphasizing recycling and reusing practices within the industry.

Moreover, find new methods and technologies to overcome the environmental burdens of cement components by extracting recycled cement from RCA or using alternative materials that substitute the cement such as fly ash, recycled plastics, limestone dust….etc.

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**Availability of data and materials** The data that support the findings of this study are available from the corresponding author upon reasonable request.

## Declarations

**Conflict of interest** The authors declare that they have no competing interests.

**Ethics approval and consent to participate** The authors assert that the manuscript is their original work and that any ideas, perspectives, innovations, and outcomes presented in the manuscript are their own, unless otherwise cited in the text. Any work of others that was utilized in the development of the ideas presented in the manuscript is clearly acknowledged within the text and properly cited at the end. Additionally, the authors state that they have given their consent for the manuscript to be published.

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