# Enhancing Construction Sustainability through the Use of Recycled Aggregates in Concrete Production

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**Abstract:**

The construction industry is a major consumer of natural resources and a significant contributor to environmental degradation, necessitating a shift towards more sustainable practices. This study comprehensively evaluates the emergy performance of concrete produced with recycled aggregates as a substitute for natural aggregates, with the aim of quantifying its potential to reduce total resource consumption and enhance sustainability within the built environment. A robust solar emergy accounting method was applied to quantify and compare all emergy inputs associated with the entire life cycle, including material extraction, processing, transportation, and the concrete production phase itself. The results clearly indicate that replacing 50% of natural coarse aggregates with recycled alternatives leads to a substantial 24.3% reduction in total emergy consumption and a 12.6% improvement in the Emergy Sustainability Index (ESI) compared to conventional natural aggregate concrete (NAC). The majority of these emergy savings are directly attributed to the avoidance of energy-intensive quarry extraction and the significantly reduced processing requirements for recycled materials. A sensitivity analysis further confirmed that the emergy advantage of recycled aggregate concrete remains significant even with increased transportation distances. These findings conclusively demonstrate that the strategic use of recycled aggregates can significantly improve the environmental performance of concrete by reducing its pressure on natural capital. This supports the transition toward more circular and resource-efficient construction practices. The study provides critical new insights and quantitative data for policymakers and industry stakeholders, highlighting the substantial emergy benefits of material substitution and informing strategies for sustainable concrete production.

**Keywords:** Sustainable construction; NAC; RAC; emergy; concrete.

## 1 Introduction

Construction is widely regarded as one of the most critical and influential production activities carried out by human societies. It plays a central role not only in shaping the built environment but also in driving economic expansion, urbanization, and improvements in living standards. Throughout history, the construction sector has been a key indicator of national development, as infrastructure such as transportation networks, residential buildings, industrial complexes, and public facilities directly contributes to social welfare and economic productivity. However, this substantial influence comes with significant environmental and resource-related consequences. The industry's reliance on vast quantities of raw materials, intensive energy use, and extensive land occupation has made it a major contributor to ecological degradation, prompting increasing global attention to its environmental footprint.

In contemporary settings, the construction industry continues to function as a capital, resource, and labor-intensive sector. It consumes millions of tons of natural materials annually and employs a substantial portion of the global workforce. Despite technological advancements, digitalization trends, and incremental improvements in project management, many construction activities especially in developing countries remain inefficient and environmentally damaging. In these regions, construction projects are frequently characterized by high levels of material waste, excessive energy consumption, outdated construction methods, and inadequate regulatory oversight. Even in developed nations, where advanced technologies and strict regulations are more prevalent, the industry still faces challenges related to environmental pollution, resource depletion, and rising costs. These persistent issues highlight the urgent need to transition toward more sustainable construction practices that reduce ecological impacts without compromising structural performance, economic feasibility, or safety.

Sustainable construction has emerged as a key concept in addressing these challenges. It refers to the integration of sustainability principles into the planning, design, execution, operation, and demolition of buildings and infrastructure. At its core, sustainable construction aims to meet present building demands while preserving the ability of future generations to meet theirs. Achieving this goal requires reducing reliance on non-renewable resources, optimizing material efficiency, and minimizing waste generation throughout a building's lifecycle. Additionally, it involves adopting energy-efficient technologies, implementing environmentally responsible engineering methods, and ensuring that construction processes adhere to both ecological and safety standards. With the support of advanced technologies, such as automation, digital modeling, and material recycling systems, construction activities can become more resource-efficient and environmentally friendly.

The need for sustainable strategies becomes particularly evident when analyzing waste generation statistics from the construction sector. According to reports published by the Australian government, construction and demolition (C&D) activities generated approximately 19 million tons of waste between 2008 and 2009. Of this amount, about 8.5 million tons were disposed of in landfills, leading to a range of environmental problems including land occupation, soil pollution, greenhouse gas emissions, and the unnecessary loss of recoverable materials [1]. Such figures illustrate the immense environmental burden associated with C&D waste and emphasize the importance of incorporating sustainability principles at every stage of a building's lifecycle from material production and construction to maintenance and eventual demolition. Indeed, the construction and demolition phases represent crucial opportunities for implementing energy-saving strategies, reducing emissions, and promoting circular economy practices within the sector.

Achieving sustainability in construction involves a broad range of approaches. These include optimizing building design to reduce material consumption, enhancing construction methodologies to minimize waste, and selecting environmentally friendly materials such as low-carbon cement, recycled aggregates, and renewable-based composites. Among all construction materials, concrete remains the most widely used due to its excellent mechanical properties, versatility, and availability. However, its production relies heavily on natural aggregates including sand, gravel, and crushed stone, which are extracted from finite geological sources. The extraction, processing, and transportation of these aggregates require substantial energy inputs and contribute to significant environmental impacts such as habitat destruction, riverbed degradation, biodiversity loss, and $CO_2$ emissions.

Despite the large quantities of concrete waste generated every year from demolished structures, only a fraction of this material is recycled and reused in new construction projects. Historically, waste concrete has been treated as construction debris rather than a valuable resource. Only in recent decades has interest grown in recycling concrete to produce recycled aggregates, driven by concerns about resource scarcity, rising material costs, and the environmental impacts of quarrying. These recycled aggregates can potentially replace natural aggregates in concrete production, offering a sustainable alternative that reduces dependence on virgin materials. However, the recycling process itself involves crushing, sorting, washing, and transporting waste concrete, all of which require additional energy and may generate their own environmental impacts. Consequently, it remains unclear whether the use of recycled aggregate concrete (RAC) results in lower total energy consumption than natural aggregate concrete (NAC) when evaluated from a lifecycle perspective.

In contrast to a review study, this paper presents an original comparative energy analysis between Natural Aggregate Concrete (NAC) and Recycled Aggregate Concrete (RAC). While data is sourced from the literature, the novelty and contribution of this work lie in the systematic application of the energy accounting method to provide a unified sustainability metric for these materials, filling a critical gap in existing research which has primarily focused on mechanical properties and traditional Life Cycle Assessment (LCA).

This uncertainty has led to increased interest in emergy analysis a holistic method for assessing the total energy and material inputs required to produce a given product or system. Emergy analysis considers not only the direct energy used in manufacturing but also all indirect energy flows embodied in materials, labor, services, and environmental inputs. This makes it particularly valuable for evaluating construction materials, whose production chains often involve complex processes and multiple resource flows. While numerous studies have examined the mechanical behavior of RAC, such as compressive strength, durability, and modulus of elasticity, far fewer have investigated its emergy performance. Existing research has provided valuable insights into concrete mix optimization, showing that appropriate proportions of recycled aggregates can maintain sufficient mechanical quality. However, the question of whether RAC actually reduces emergy consumption and therefore contributes to greater sustainability remains insufficiently explored.

The present study seeks to fill this research gap by systematically evaluating the emergy consumption associated with RAC and NAC under identical mix ratio conditions. By quantifying all direct and indirect energy inputs involved in producing concrete with particular emphasis on aggregate extraction, processing, and transportation this study aims to provide a comprehensive comparison of the sustainability performance of both materials. A major challenge in this analysis lies in accurately quantifying the emergy contributions of diverse inputs, such as machinery operation, fuel use, industrial processing, and material transportation over varying distances. Standardizing these components within an emergy framework requires detailed data collection, methodological consistency, and careful evaluation of system boundaries.

Nevertheless, emergy analysis offers a powerful tool for understanding the full ecological cost of construction materials. By applying this technique, the current study aims to determine whether the use of recycled aggregates offers a tangible sustainability benefit beyond conventional assumptions. The findings of this research will not only contribute to academic knowledge on construction material sustainability but also support policymakers, engineers, and construction practitioners in making informed decisions regarding material selection. This study provides critical new insights... construction practices. Ultimately, promoting the adoption of RAC has the potential to reduce waste generation, conserve natural resources, lower energy consumption, and advance the broader goals of sustainable construction.

## 2 Background

According to the studies of Stahel (1997), Geissdoerfer et al. (2017), and Tukker (2015), the construction and demolition processes of a building can be viewed as an ecological cycle of resources. Achieving environmental sustainability requires taking action at the critical points within this cycle [2, 3, 4]. Today, with the growing scale of engineering construction, there is a continuous search for practices that can minimize negative environmental impacts [5, 6]. Experts around the world are increasingly concerned with green construction and the environmental effects of using recycled and environmentally friendly materials [7, 8].

Several researchers have conducted feasibility studies on the use of recycled aggregates in concrete structures [9, 10]. These studies generally indicate that the incorporation of recycled aggregate concrete (RAC) has a negligible effect on the mechanical properties and durability of concrete. For instance, Gao et al. (2019) reported that using crushed brick as coarse aggregate in concrete results in only a 7% reduction in compressive strength compared to conventional concrete made with natural aggregates, while the unit weight of the concrete is reduced by approximately 9.5% [11]. These findings suggest that the use of recycled materials can reduce structural weight and the consumption of natural resources without significantly compromising mechanical performance.

Previous studies have also emphasized the importance of waste management and recycling in construction and demolition projects. Al Hallaq et al. (2022) conducted a risk analysis of construction and demolition waste in the Gaza Strip and highlighted that proper planning for the reuse of materials can substantially reduce the environmental and economic impacts of construction projects [9]. Similarly, Hansen (1992) reviewed various methods for recycling demolished concrete and masonry and proposed strategies for substituting natural aggregates with recycled materials [10]. Overall, the existing evidence suggests that recycled aggregates can serve as a viable alternative to natural aggregates in modern concrete structures, offering both environmental and economic benefits while maintaining adequate structural performance.

More recently, several studies have focused on the use of crushed brick in concrete. In the study by Brencich et al. (2024), different amounts of polymer additives were incorporated into recycled aggregates to evaluate the properties of the resulting concrete. The authors concluded that polymer-modified concrete not only maintained comparable compressive and flexural strength but also showed improved waterproofing and frost resistance, along with a lower modulus of elasticity [12]. Ferreira et al. (2024) reported that, based on tests of chloride-ion ingress, creep behavior, and freeze-thaw resistance, the durability of recycled aggregate concrete is not a critical concern [13]. According to Kenai et al. (2002), when using recycled fine and coarse aggregates, the proportion of fine aggregate should be carefully controlled to account for water absorption, shrinkage, and water permeability [14].

Shah et al. (2020) made significant progress in this area of research. They attempted to replace a portion of Portland cement with crushed masonry and investigated the effect of brick powder on the compressive strength of mortar [15]. According to Silva (2016), the use of natural sand along with small amounts of recycled aggregates in mortar results in mechanical properties that are relatively similar, with comparable bulk specific gravity and water absorption rates [16]. Therefore, the incorporation of recycled aggregates holds considerable scientific research value.

Several scholars have conducted research on strengthening recycled aggregates. They primarily aimed to enhance the performance of recycled aggregates through chemical and physical methods. Guo et al. (2015) treated recycled aggregates with a 6% silicone solution. After testing, both the water absorption rate and the crushing index improved, reaching levels comparable to those of natural aggregates. Compared with ordinary concrete, concrete incorporating recycled aggregates generally exhibits lower tensile properties [17]. Qin et al. (2012) added 1.2 kg/m³ of polypropylene fibers during preparation, resulting in a 13% increase in the tensile strength of the recycled concrete, indicating that tensile fiber additives are also effective for recycled concrete [18]. Xiao et al. (2012) proposed a new technology for aggregate treatment, using microwave heating to remove mortar adhered to the surface of recycled aggregates, thereby improving their performance [19]. Research results show that recycled aggregates treated by this method exhibit significant improvements in crushing index, porosity, water absorption, and other indicators, producing concrete with strength closer to that of natural aggregate concrete (NAC). This method also provides a novel approach for the treatment of recycled aggregates.

In 2014, Quattrone et al. presented research on the production of high-quality recycled aggregates. In their study, they analyzed current mainstream production technologies, the energy consumption of these processes, and the carbon dioxide emissions associated with each method. Besides the Ordinary Recycling Process (ORC), current methods are mainly divided into mechanical treatments and thermo-mechanical treatments. Mechanical treatments include the Eccentric Rotor Crusher (ERC), Screw Abrading Crusher (SAC), and Compression & Impact Process

(C&I). Thermo-mechanical treatments include Heating and Sorting (HS-RK), Heating and Rubbing (HR-F), and Heating and Rubbing (HR-M). The results indicate that recycled aggregates produced by thermo-mechanical treatments consume more energy and emit significantly higher levels of carbon dioxide several times that of mechanical treatments. However, coarse aggregates treated by thermo-mechanical methods show significant improvements in water absorption and porosity, making them fully suitable to partially replace natural aggregates in concrete [20].

Recent studies have continued to refine the understanding of RACs environmental impact and technical performance. Research has increasingly focused on life-cycle assessment (LCA) to quantify the carbon reduction potential of high-quality recycled aggregates, though often highlighting the trade-offs with energy consumption during processing [21, 22]. Concurrently, significant advancements have been made in advanced treatment methods for improving the quality of recycled aggregates, such as carbonation treatment and bio-deposition, which enhance their microstructure and reduce water absorption [23, 24]. Furthermore, comprehensive reviews have consolidated the state-of-the-art, confirming the mechanical feasibility of RAC while also pointing to the need for more holistic sustainability metrics that account for broader ecosystem contributions [25, 26]. While the existing body of research, both historical and contemporary, has firmly established the mechanical viability of RAC, a critical gap remains in systematically quantifying its holistic energy footprint using a unified metric like emergy [27]. The emergy methodology uniquely captures the direct and indirect environmental support for resource generation, offering a systems-ecology perspective that complements traditional LCA. This study aims to fill this gap by providing a direct, comparative emergy analysis between NAC and RAC, thereby building upon and extending the foundational work of past researchers.

## 3 Methodology

This section outlines the energy value analysis methodologies employed in the present study. This study employs a comparative energy analysis framework to evaluate the environmental performance of NAC and RAC. The methodology is structured not as a literature review, but as a quantitative analytical process based on secondary data, standardized into a unified solar energy equivalent (sej) for robust comparison. The specific samples to be analyzed will be clearly defined, and their key characteristics and selection criteria will be described. Furthermore, the origins of the data utilized in the analysis will be explicitly stated to ensure transparency and establish the credibility of the research findings.

### 3.2 Emergy Analysis Method

Emergy Emergy is defined as the sum of all direct and indirect energy inputs, expressed in solar energy equivalents, required to generate a product or provide a service [28]. As a significant advancement in systems ecology, emergy analysis offers a powerful tool for quantifying and comparing different categories of energy on a common basis. The primary advantage of this method, and its application in this study, is its ability to resolve the challenge of unifying disparate substances and energy forms which traditionally possess different units into a single, standardized metric.

This metric, often termed Solar Emergy, represents the total energy, both past and present, embodied in an object or service, with its unit of measurement being the solar emjoule (sej) [28]. The conversion to this universal standard is achieved using solar transformity, a central concept defined as the solar emergy required to generate one unit of available energy (or mass) of a given type. Its units are consequently sej/J or sej/g. By applying the appropriate transformity values, diverse flows of energy and materials from sunlight and fossil fuels to human labor and minerals can be translated into equivalent solar emjoules, enabling comprehensive and unified calculations within a holistic ecological-economic framework.

### 3.2 Sample Specification

To ensure a valid and accurate comparison between Natural Aggregate Concrete (NAC) and Recycled Aggregate Concrete (RAC), key variables must be controlled. This study conducts a comparative emergy analysis of the complete life cycle for both NAC and RAC. A critical variable is compressive strength, as it directly influences the concrete's mixing ratio. Therefore, to establish a consistent baseline, one cubic meter of concrete with a standard compressive strength of 25 MPa is selected as the functional unit for analysis. The specific mixing ratio for this benchmark is 0.44:1:1.42:3.17, corresponding to 175 kg of water, 398 kg of cement, 566 kg of fine aggregate, and 1261 kg of coarse aggregate, resulting in a total mass of 2400 kg. For the RAC scenario, the coarse aggregate consists of a 50% blend of natural and recycled aggregate. This proportion is selected based on established research, which confirms that with proper processing, concrete incorporating recycled aggregate can reliably achieve the required structural strength and performance. The emergy analysis itself is structured by categorizing the energy inputs into five distinct phases, which are calculated separately to ensure precision and transparency: Cement Production, Transportation, Recycled, Aggregate Production, Raw Material Acquisition (for aggregates), Concrete Production (mixing and curing).

### 3.3 Data Collection

In this study, the energy consumed for producing raw materials and the corresponding solar transformities are derived from existing literature. Data regarding the materials and equipment used in cement production are sourced from a case study [29]. For transportation-related emergy consumption, information on equipment and human resources is obtained from a previous study [30]. The transportation distance is estimated based on the distance between suppliers and the construction site. Additional energy input data for concrete production are collected from research findings [30]. Concerning the production of recycled aggregates, the specific quantities of electricity and diesel consumption are gathered from a case study [20]. The varying solar transformities of different forms of energy and materials are compiled from multiple research sources [28, 30, 33, 35, 36].

### 3.4 Limitations and Uncertainty Analysis

This emergy analysis is based on secondary data sourced from case studies and published literature, which imposes certain limitations regarding data specificity and variability. To evaluate the uncertainty associated with key parameters such as transportation distance, a basic sensitivity analysis was performed. The results show that varying the transportation distance by ±25% alters the total emergy values for both NAC and RAC by less than 1.5%. This finding demonstrates that the core finding of RAC's emergy reduction advantage remains robust despite such fluctuations. Consequently, the results of this study should be viewed as a robust comparative assessment rather than an absolute measure applicable to a specific geographical context.

## 4 Result Analysis

Based on the five energy consumption categories presented in the methodology section, it is necessary to calculate each category separately in order to determine the total emergy consumption during the concrete production process. Since the primary difference between recycled aggregate concrete (RAC) and natural aggregate concrete (NAC) lies in the type of coarse aggregate used, the energy consumed in cement manufacturing and concrete mixing is assumed to be identical for both types. It is further assumed that the same cement supplier and the same natural aggregate supplier are used for both RAC and NAC, ensuring consistent production conditions. This separate calculation allows researchers to accurately identify the contribution of each component to the overall emergy consumption and to assess more precisely the environmental implications of substituting natural aggregates with recycled ones. Ultimately, this approach provides clearer insight into the potential benefits and challenges associated with using recycled materials in concrete production.

### 4.1 Emergy of Cement Production

The production of cement requires the use of various forms of energy and materials, including raw materials and their extraction, packaging, water resources, and human labor. Data on energy consumption and other inputs were obtained from a cement manufacturing facility in Italy [29], which has an annual output of 715,000 tons of different cement types. Information on the raw materials used in cement production was sourced from Cement Manufacturing – Raw Materials [35]. In this study, it is assumed that producing one cubic meter of concrete requires 398 kg of cement. The emergy associated with packaging materials and human labor was derived from the case study presented in [30]. Solar transformities used in data processing were taken from several research sources [28, 33, 35]. The emergy required to produce 398 kg of cement was calculated as $1.1986 \times 10^{15}$ sej. The detailed emergy values for producing one ton of cement are provided in Table 1.

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### 4.2 Emergy of transportation

In assessing the emergy consumption associated with transportation, equipment depreciation, fuel use, and human labor are the primary factors considered. It is assumed that transportation is carried out using a 25-ton truck, with each trip delivering raw materials sufficient to produce 20 tons of concrete. Data related to equipment depreciation were obtained from previous research [23]. The truck's fuel consumption is assumed to be 0.4 L per kilometer, and the transportation distance from each supplier to the construction site is set at 20 km. In this study, the production of NAC requires materials from three suppliers: sand, aggregate, and cement. For RAC, the recycled aggregate producer must also be included. Consequently, the total transportation distance for NAC materials is assumed to be 60 km, while for RAC materials it is 80 km. Human labor associated with transportation is estimated as 6 working hours per 100 km, based on the results reported in [30].

Based on the calculations, the total transportation emergy consumption is 84.4 × $10^{11}$ sej for recycled-aggregate concrete and 63.4 × $10^{11}$ sej for natural-aggregate concrete. The detailed emergy values calculated per kilometer are presented in Table 2.

Table 1. Emergy of cement production

| Item | Input | Solar transformity | Emergy (sej) |
|---|---|---|---|
| Energy inputs | | | |
| Electricity | $4.10 * 10^8$ J | $2.07 * 10^5$ sej/J | $8.49 * 10^{13}$ |
| Pet coke | $3.23 * 10^9$ J | $1.13 * 10^5$ sej/J | $3.65 * 10^{14}$ |
| Oil | $8.71 * 10^7$ J | $9.3 * 10^4$ sej/J | $8.10 * 10^{11}$ |
| Materials | | | |
| Limestone | $1.12 * 10^6$ g | $1.68 * 10^9$ sej/g | $1.88 * 10^{15}$ |
| Clay | $2.64 * 10^5$ g | $1.68 * 10^9$ sej/g | $4.44 * 10^{14}$ |
| Other | $1.26 * 10^5$ g | $1.68 * 10^9$ sej/g | $2.12 * 10^{14}$ |
| Quarrying explosive | 30.5 g | $6.38 * 10^8$ sej/g | $7.72 * 10^9$ |
| Packing | $1.47 * 10^{13}$ sej | | $1.47 * 10^{13}$ |
| Water input | $4.45 * 10^5$ g | $1.95 * 10^6$ sej/g | $8.67 * 10^{11}$ |
| Human work | $9.41 * 10^{11}$ sej | | $9.41 * 10^{11}$ |

Table 2. Emergy of transportation

| Item | Input | Solar transformity | Emergy (sej) |
|---|---|---|---|
| Deprecation | $9.42 * 10^{10}$ sej | - | $9.42 * 10^{10}$ |
| Diesel | $1.44 * 10^7$ J | $1.13 * 10^5$ sej/J | $1.63 * 10^{12}$ |

| | | | |
|---|---|---|---|
| Human work | $3.14 * 10^4$ J | $1.24 * 10^7$ sej/J | $3.89 * 10^{11}$ |

## 4.3 Emergy of Recycled Aggregate Production

To support the commercialization of recycled aggregate production, the Ordinary ORC method is selected for processing the recycled material. To ensure that the resulting recycled-aggregate concrete achieves adequate strength, 50% of the natural aggregate is replaced with recycled aggregate. Consequently, each cubic meter of recycled-aggregate concrete contains 630 kg of recycled aggregate and 630 kg of natural aggregate. The energy input data for recycled aggregate production were obtained from a case study on recycled aggregate treatment processes [20]. Based on the calculations, producing one cubic meter of RAC requires $47.3 \times 10^{11}$ sej of solar emergy. The detailed emergy values associated with the production of one ton of recycled aggregate are presented in Table 3.

## 4.4 Emergy of Materials

According to the M25 concrete mix design, producing one cubic meter of concrete requires 175 kg of water, 398 kg of cement, 566 kg of fine aggregate, and 1,261 kg of coarse aggregate. The only difference between NAC and RAC lies in the coarse aggregate component, where 50% of the natural aggregate is replaced with recycled aggregate. For water, fine aggregate, and natural coarse aggregate, only the potential solar emergy embodied in the materials is considered. The solar emergy associated with cement and recycled coarse aggregate has already been calculated in previous sections. Based on these values, the total emergy associated with material use is $4.2697 \times 10^{15}$ sej for NAC and $3.2160 \times 10^{15}$ sej for RAC. The detailed emergy calculations for the concrete materials are presented in Tables 4 and 5.

## 4.5 Emergy of Concrete Production

In the concrete production process, beyond the emergy associated with transportation and materials, additional emergy inputs are required for labor, site operations, equipment use, and the fuel consumed during machine operation. Based on the energy inputs reported for concrete production in [23], producing 2.4 tons of concrete requires an additional emergy input of 448.3 × $10^{11}$ sej. The detailed emergy consumption associated with producing one ton of concrete is presented in Table 6.

Table 3. Emergy for recycled aggregates production

| Item | Input | Solar transformity | Emergy (sej) |
|---|---|---|---|
| Diesel | $1.23 * 10^7$ J | $1.13 * 10^5$ sej/J | $1.39 * 10^{12}$ |
| Electricity | $2.95 * 10^7$ J | $2.07 * 10^5$ sej/J | $6.11 * 10^{12}$ |

Table 4. Emergy of the material for the production of NAC

| Item | Input (g) | Solar transformity | Emergy (sej) |
|---|---|---|---|
| Water (7.3%) | $1.75 * 10^5$ | $1.95 * 10^6$ (sej/g) | $3.41 * 10^{11}$ |
| Cement (16,.6%) | $3.98 * 10^5$ | - | $1.20 * 10^{15}$ |
| Sand (23.6%) | $5.66 * 10^5$ | $1.68 * 10^9$ (sej/g) | $9.51 * 10^{14}$ |
| Natural Aggregate (52.5%) | $12.61 * 10^5$ | $1.68 * 10^9$ (sej/g) | $2.12 * 10^{15}$ |

Table 5. Emergy of the material for the production of RAC

| Item | Input (g) | Solar transformity | Emergy (sej) |
|---|---|---|---|
| Water (7.3%) | $1.75 * 10^5$ | $1.95 * 10^6$ (sej/g) | $3.41 * 10^{11}$ |
| Cement (16,.6%) | $3.98 * 10^5$ | - | $1.20 * 10^{15}$ |
| Sand (23.6%) | $5.66 * 10^5$ | $1.68 * 10^9$ (sej/g) | $9.51 * 10^{14}$ |
| Natural Aggregate (56.3%) | $6.31 * 10^5$ | $1.68 * 10^9$ (sej/g) | $1.06 * 10^{15}$ |
| Recycled Aggregate (26.2%) | $6.31 * 10^5$ | - | $4.73 * 10^{12}$ |

Table 6. Emergy required for NAC or RAC production

| Item | Input (sej) |
|---|---|
| Human work | $2.26 * 10^{12}$ |
| Fuel | $1.42 * 10^{13}$ |
| Plant and machinery | $2.22 * 10^{12}$ |

### 4.6 Discussions

The emergy consumption of the two concrete types (NAC and RAC) is illustrated in the flow charts presented in Figures 1 and 2, where all values are expressed in sej × $10^{11}$. In these diagrams, the arrows represent the direction of emergy flow. For example, the solar emergy embodied in the natural raw materials enters the cement production process, after which the total emergy accumulated throughout cement manufacturing is transferred into the cement material itself. Ultimately, the emergy associated with material production, the additional emergy inputs required for the concrete manufacturing process, and the transportation-related emergy are aggregated to determine the total emergy needed to produce one cubic meter of concrete.

The results clearly demonstrate that the majority of emergy consumption is concentrated in the production of materials. Calculations indicate that material-related emergy accounts for approximately 98.8% of the entire production process, including both the extraction of raw materials and their initial processing. In contrast, the emergy contributions from concrete production operations and transportation are comparatively negligible. Consequently, the sustainability of concrete production is largely determined by the emergy intensity of natural raw materials. To highlight this effect, the emergy distribution of NAC and RAC materials is visualized using ring diagrams (Figures 3 and 4).

A comparison of the two diagrams shows that, in NAC, coarse aggregates account for 49.6% of total material emergy consumption. Therefore, reducing the emergy intensity associated with coarse aggregates has a disproportionately large influence on improving the sustainability of concrete production. Unlike the high emergy demand of cement and natural aggregates, the emergy associated with recycled aggregate production is minimal. This substantially lowers the emergy share of coarse aggregates from 49.6% in NAC to 33.1% in RAC. As a result, incorporating recycled aggregates significantly reduces the overall emergy required for production. In fact, producing M25 RAC lowers emergy consumption by 24.3% compared with NAC.

These findings are consistent with recent Life Cycle Assessment (LCA) studies. For instance, Xing et al. (2023) reported notable reductions in the global warming potential (GWP) of RAC, although their system boundary differed from ours [37]. While LCA primarily focuses on environmental emissions and energy use, the emergy approach adopted in this study offers a complementary perspective by accounting for the cumulative environmental contribution of all natural resources involved. Thus, emergy analysis provides an integrative metric that helps assess the broader ecological implications of adopting recycled aggregates in concrete production.

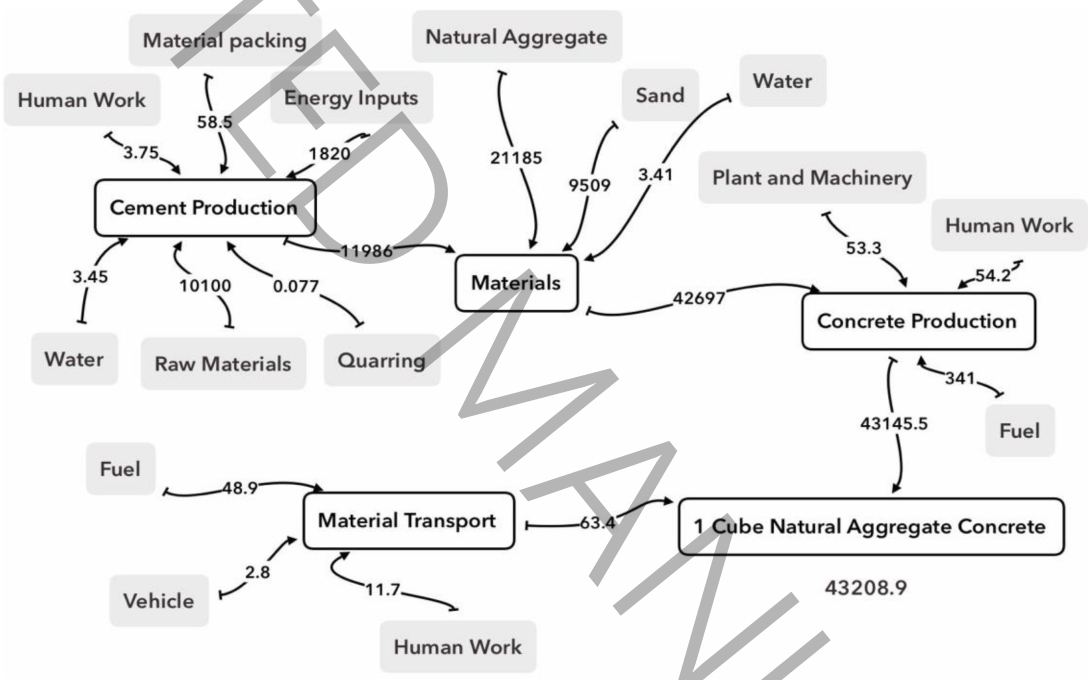


Figure 1. Emergy diagram of NAC production

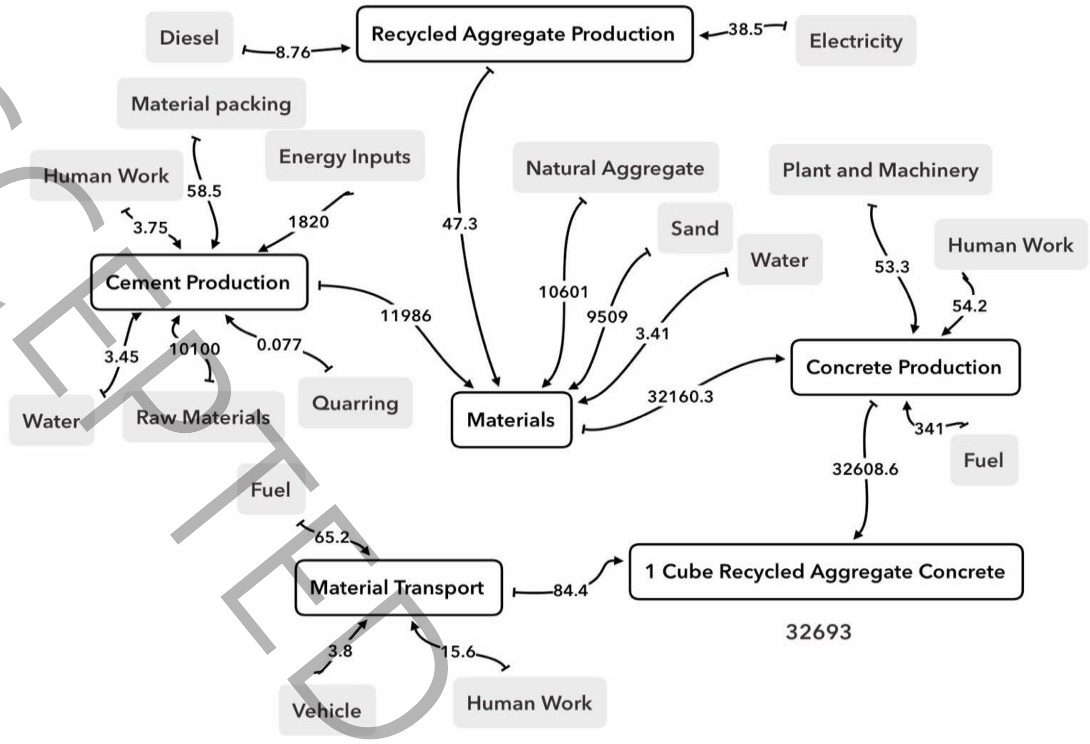


Figure 2. Emergy diagram of RAC production

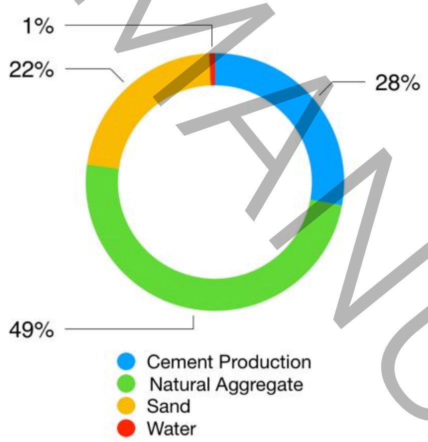


Figure 3. Proportion of NAC materials

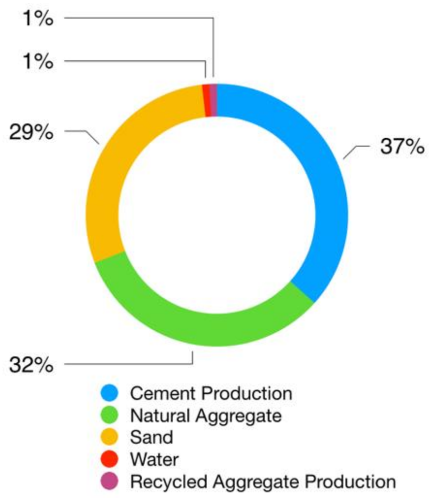


Figure 4. Proportion of RAC materials

## 5 Conclusions

The primary scientific significance of this study is its demonstration that a 50% replacement of natural coarse aggregates with recycled alternatives can lead to a substantial 24.3% reduction in total energy consumption. This finding provides a robust, quantifiable foundation for promoting RAC in sustainable construction. By utilizing the energy methodology, this research offers a holistic ecological perspective that complements traditional assessments, thereby making a novel contribution to the field of sustainable construction materials, particularly natural coarse aggregates. In comparison, the emergy required to produce recycled coarse aggregates is relatively minimal, especially when juxtaposed with the high potential solar emergy embedded in natural aggregate extraction and processing.

A central finding of this work is that substituting only 50% of natural coarse aggregates with recycled alternatives can reduce the total emergy required for concrete production by approximately 24.3%. This demonstrates the significant environmental advantage of RAC, underscoring its potential to lower the ecological footprint of construction materials while contributing to resource efficiency and economic savings. The reduction in emergy demand is particularly impactful because coarse aggregates represent nearly half of the total material-related emergy in NAC. Consequently, even partial replacement with recycled aggregates yields substantial sustainability benefits. Although this study primarily addresses coarse aggregates, it highlights the need for further research into the inclusion of fine recycled aggregates, such as recycled sand. Incorporating these materials in future analyses could provide a more holistic evaluation of emergy savings and reinforce the overall environmental benefits of RAC, particularly in large-scale or high-volume construction projects where fine aggregates constitute a considerable portion of total material use.

The findings also emphasize the dominant role of cement in the emergy profile of concrete, accounting for nearly 50% of total material emergy. This observation underscores the urgency of innovating cement production technologies to improve sustainability. Potential strategies include the adoption of alternative binders, the use of supplementary cementitious materials (e.g., fly ash, slag, or calcined clay), and enhancements in energy efficiency during cement manufacturing. Optimizing both the cement component and the aggregate composition simultaneously could result in even greater reductions in emergy, carbon emissions, and overall environmental impact.

In conclusion, this study confirms that the strategic incorporation of recycled aggregates is a highly effective approach for reducing the environmental burden of concrete production. RAC not only offers a viable pathway toward resource conservation and energy efficiency but also aligns with global goals of sustainable construction. Future research should extend this emergy analysis to include the full spectrum of concrete materials, integrate lifecycle cost assessments, and evaluate long-term performance metrics. Such investigations will strengthen the evidence base for policy development and decision-making, ultimately promoting the adoption of greener, more sustainable construction practices worldwide.

## References


[1] Hyder Consulting, 2011. Construction and demolistion waste status report, management of construction and demolistion waste in Australia. Department of the Environment and Energy, Australia Government.

[2] Stahel, W.R., 1997. The service economy: 'wealth without resource consumption? Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, 355(1728), pp.1309-1319.

[3] Geissdoerfer, M., et al. (2017). The Circular Economy, A new sustainability paradigm? Journal of Cleaner Production, 143, 757-768.

[4] Tukker, A. (2015). Product services for a resource-efficient and circular economy, a review. Journal of Cleaner Production, 97, 76-91.

[5] Cole, R.J., 2010. Emerging trends in building environmental assessment methods. Building Research & Information, 26(1), pp.3-16.

[6] Hsueh, S. L. and Yan, M. R., 2011. Enhancing Sustainable Community Developments A Multi-criteria Evaluation Model for Energy Efficient Project Selection. Energy Procedia. 5: 135-144.

[7] Humbal, A., Chaudhary, N., Pathak, B. (2023). Urbanization Trends, Climate Change, and Environmental Sustainability. In: Pathak, B., Dubey, R.S. (eds) Climate Change and Urban Environment Sustainability. Disaster Resilience and Green Growth. Springer, Singapore.

[8] Brychkov, D., Goggins, G., Doherty, E. 2023. A systemic framework of energy efficiency in schools: experiences from six European countries. Energy Efficiency 16-21.

[9] Al Hallaq, K. A., Hamad, R. J., Tayeh, B. A., and Nassar, S. S. 2022. Risk analysis and waste management for construction and demolition projects in the Gaza strip. Jordan Journal of Civil Engineering, 16(3).

[10] Hansen, T.C., 1992. Recycling of demolished concrete and masonry. CRC Press.

[11] Gao, D., Jing, J., Chen, G., Yang., L, 2019. Experimental investigation on flexural behavior of hybrid fibers reinforced recycled brick aggregates concrete. Construction and Building Materials, 227(10).

[12] Brencich, A., Dubesti, A., and Ali Akbari Hamed, F. 2024. Structural Concrete from 100% Recycled Aggregates. Applied Sciences, 14(24).

[13] Ferreira, M. d. P., Santos, K. D. d., Pereira Filho, M. J. M., & Cordeiro, L. d. N. P. 2024. Effect of Recycled Concrete Aggregates on the Concrete Breakout Resistance of Headed Bars Embedded in Slender Structural Elements. Buildings, 14(7).

[14] Kenai, S., Debieb, F. and Azzouz, L., 2002. Mechanical properties and durability of concrete made with coarse and fine recycled concrete aggregates. In Challenges of Concrete Construction: Volume 5, Sustainable Concrete Construction: Proceedings of the International Conference held at the University of Dundee, Scotland, UK on 9–11 September 2002 (pp. 383-392). Thomas Telford Publishing.

[15] Shah V, Parashar A, Medepalli S, Bishnoi S 2020. Prediction of carbonation using reactivity test methods for pozzolanic materials. Advances in Cement Research, Vol. 32 No. 7 pp. 297–306.

[16] Silva, R. V., Brito, J. D., Dhir, R. K., 2016. Performance of cementitious renderings and masonry mortars containing recycled aggregates from construction and demolition wastes. Construction and Building Materials, 105(15), pp.400-415.

[17] Guo, Y.X., Li, Q.Y., Wang, W.Q., Niu, J.Y., Kong, Z., 2015. Research on Quality Improvement Technology of Recycled Coarse Aggregate. Concrete, (6), pp.134-138.

[18] Qin, F. and Brosseau, C., 2012. A review and analysis of microwave absorption in polymer composites filled with carbonaceous particles. Journal of applied physics, 111(6), p.4.

[19] Xiao, J.Z., Wu, L., Fan, Y.H., 2012. Microwave heating regeneration coarse aggregate modification test [J]. Concrete, (7), pp.55-57.

[20] Quattrone, M., Angulo, S.C. and John, V.M., 2014. Energy and $CO_2$ from high performance recycled aggregate production. Resources, Conservation and Recycling, 90, pp.21-33.

[21] Marinković, S., Carević, V., & Ignjatović, I. (2023). Life cycle assessment of concrete with recycled aggregates: A systematic review and update. Journal of Cleaner Production, 382, 135246.

[22] Kurda, R., Silvestre, J. D., & de Brito, J. (2020). Life cycle assessment of concrete made with recycled aggregates: influence of the methodology. International Journal of Life Cycle Assessment, 25, 1801–1816.

[23] Kumar, R., Dhangar, N., & Singh, S. K. (2021). Enhancing the properties of recycled aggregate concrete through advanced treatment techniques: A review. Construction and Building Materials, 302, 124197.

[24] Xiong, B., Li, T., Li, J., & Zhang, Y. (2022). An emergy-based sustainability evaluation of recycled aggregate concrete in China. Environmental Science and Pollution Research, 29(58), 88281-88297.

[25] Wang, B., Yan, L., Fu, Q., & Kasal, B. (2021). A comprehensive review on recycled aggregate concrete. Composites Part B: Engineering, 221, 109000.

[26] Silva, R. V., de Brito, J., & Dhir, R. K. (2021). Availability and processing of recycled aggregates within the framework of circular economy. Proceedings of the Institution of Civil Engineers - Waste and Resource Management, 174(2), 39-55.

[27] Tian, Y., Zhang, J., & Li, G. (2022). A comparative emergy analysis of sustainable concrete mixes incorporating recycled concrete aggregates and supplementary cementitious materials. Journal of Industrial Ecology, 26(4), 1450-1463.

[28] Odum, H.T., 1996. Environmental accounting: emergy and environmental. Decision Making (p. 370). New York: Wiley.

[29] Potgieter, J. H. 2012. An Overview of Cement production: How "green" and sustainable is the industry? Environmental Management and Sustainable Development, 1:2.

[30] Pan, H., Zhang, X., Wu, J., Zhang, Y., Lin, L., Yang, G., Deng, S., Li, L., Yu, X., Qi, H., Peng, H. 2016. Sustainability evaluation of a steel production system in China based on emergy. Journal of Cleaner Production. 112(2), pp. 1498-1509.

[31] Odum, H.T., 1996. Environmental Accounting: Emergy and Environmental Decision Making. Wiley, New York, NJ.

[32] Brown M.T., Arding J., 1991. Transformities Working Paper. Center for Wetlands, University of Florida, Gainesville, Florida, FL.

[33] Pulselli, R.M., Rustici, M. and Marchettini, N. 2007. An Integrated Framework for Regional Studies: Emergy Based Spatial Analysis of the Province of Cagliari. Environ Monit Assess 133, 1–13.

[34] Winter, N.B., 2012. Understanding cement: An introduction to cement. production, cement hydration and deleterious processes in concrete. Microanalysis Consultants.

[35] Scariot, M. R., Dal-Bó, V., Arrieche, L. D. S., 2024. Emergy accounting of coffee husks for the generation of energy. Fuel. 362: 130862.

[36] Ulgiati, S., Odum, H.T., Bastianoni, S., 1994. Emergy use, environmental. loading and sustainability. An emergy analysis of Italy. Ecol. Model. 73, 215–268.

[37] Xing, W., WY Tam, V., Le, J. N., Hao, J. L., and Wang, J., 2023. Life cycle assessment of sustainable concrete with recycled aggregate and supplementary cementitious materials. Resources, Conservation and Recycling, 193: 106947.