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CIRCULAR ECONOMY APPROACHES MODEL FOR CERAMIC-WASTE AGGREGATE CONCRETE

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Abstract

Substitution of virgin aggregate with processed ceramic waste (CW) may support circular building. Yet, a high substitution does not assure mechanically feasible or ecologically preferable concrete. Here, we provide a quantitative Circular Economy Approaches Model that combines material-loop closure, cradle-to-gate environmental indicators, aggregate-system economics, and mechanical-performance protections for ceramic-waste aggregate concrete. The experimental database was obtained from published work and consisted of a natural-aggregate control and eight mixes where the CW replaced 25–100% of the fine or coarse aggregate individually. Mass-balance equations evaluated ceramic-waste diversion, avoided virgin-aggregate consumption, and circular material percentage for a functional unit of 1 m3 of concrete, whereas benchmark-calibrated computations calculated global-warming potential, embodied energy, and aggregate-system cost. The measured 7- and 28-day compressive, splitting-tensile and flexural strengths were used in a control normalized mechanical-performance index. The findings indicated that the best-balanced combination is FA3 with 75% substitution of ceramic-sand. FA3 reached compressive strength of 39.14 MPa, splitting-tensile strength of 3.50 MPa, flexural strength of 4.38 MPa and the greatest mechanical-performance index of 1.117 after 28 days. The

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combination reused 450 kg/m³ of CW, substituting an equal amount of natural sand and reaching a circular material share of 32.14%. The benchmark-calibrated scenario resulted in a 17.71% reduce in global-warming potential, a 15.07% decrease in embodied energy, and a 38.63% reduction in aggregate-system cost compared to the control. CA4, the option with the best mass-based circularity and theoretical environmental-economic savings, failed the required mechanical safeguard, thereby illustrating that maximal waste incorporation is not a sufficient optimization criteria.

Keywords: Circular economy model (CEM); ceramic waste (CW); recycled aggregate concrete.

Introduction

Larger amounts of waste produced throughout ceramic manufacturing are being dumped into the environment as the ceramic industry continues to grow quickly. The industry of ceramic attempts to preserve environmental sustainability are hampered by this, which has important environmental ramifications [1]. Industrial waste accounts for approximately 31 percent of ceramic plant output, which causes serious environmental contamination and necessitates the use of a large area of dry land for disposal, especially once the waste has dried. It is crucial for the building sector to promptly dispose of and use ceramic waste in order to solve this problem [2]. Since there is at present no effective way to handle or recycle the polishing powder produced from ceramic waste (WC), it is frequently thrown away in landfills or allowed to build up in open spaces. Due of the substantial environmental effects of this activity, a different strategy is needed to solve the problem. Furthermore, usage of energy, management of wastewater, and dust and emissions of greenhouse gases are significant problems associated with the production of sanitary ware and ceramic tiles [3]. Recent research indicates that ceramic tile powder particles are low-cost waste materials that

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might assist address the issue of solid waste disposal while also preventing environmental pollution [4]. Utilizing CW offers a viable way to improve environmental protection and trash-recycling programs [5].

The most practical method of striking a balance between environmental and economic benefits is the current practical strategy of recycling CW during manufacture [6], [7], [8]. The utilization of industrial waste, including CW, in the production of cement has been encouraged by international standards in recent years due to the benefits it offers in science, technology, and the environment, especially the waste durability [9]. The development of environmentally beneficial alternatives to sand or gravel as natural aggregates by using CW, which is readily accessible and recyclable, is required due to the growing amount of land used annually to dispose of traditional aggregates [10]. Utilized ceramic sludge makes up a significant portion of the waste produced by the ceramic industry. This trash has traditionally been disposed of in landfills, which has had detrimental effects on the environment. As a result, several research have shown that specialized mixtures of different kinds of CW have the potential to create eco-friendly building materials and support the growth of eco-friendly construction industry practices [11]. Since these strategies have been shown to benefit the environment, they are crucial elements of sustainable development, which is especially important for the building sector [11]. This finding makes it possible to thoroughly examine the complex needs of recycling ceramic tile waste, which need for further investigation. This may improve the qualities of cement mortar and result in an efficient environmental protection approach [12]. Utilizing CW has many benefits, one of which is that it promotes environmental sustainability. This is due to the fact that it lowers emissions of carbon dioxide (CO2) and consumption of energy related to the manufacture of binder. It also lessens the depletion of landscapes utilized in the industrial manufacture of aggregates and binders, which lowers the CO2 releases of mining operations that usually harm riverbeds and landscapes. A kilogram of cement clinker has an

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energy impact of around 850 k/cal. Since cement makes up over 45% of the cost of concrete, substituting any kind of industrial effluent or byproduct for cement in concrete results in significant energy and environmental savings. Additionally, this may significantly lower the price of concrete [13].

By reducing the energy consumption and CO2 releases associated with binder production, also by attempting to reduce the raw materials exploitation for the industrial production of binders and aggregates, using CW helps the environment by reducing the CO2 releases associated with the devastation of riverbeds and the landscape caused by mining operations [14]. Furthermore, recycling and reusing CW to make concrete, which has been shown to lower greenhouse gas emissions, is one of the documented strategies to lessen the effect of CW [11], [15]. The enormous quantity of CW that is produced every day is successfully compensated by recycling it into construction materials, which addresses this reusability issue. This not only eases the burden on the ceramic industries but also lowers waste, electricity consumption, and production costs in industrial facilities. Additionally, this method may enhance the quality of the material [16]. When employed as a replacement element in concrete, CWP has been shown to assist reduce environmental harm, despite its original ability to contaminate air, water, and soil [17], [18]. Furthermore, it reduces the demand for both virgin cement [19] and structural concrete that replaces Portland cement with 20–40% waste [7]. The ceramic industry's waste management problems may be resolved and a sustainable concrete market can be promoted by putting CW recycling strategies into practice. This lessens the need for nonrenewable resources like aggregates and cement while reducing the environmental risks associated with landfills [20]. Reusing this trash to make ceramics might lower CO2 releases and protect the environment [21]. In order to solve global environmental concerns, recycling CW via ceramic and power-generation enterprises is crucial [22].

The construction sector remains a major contributor to resource depletion and climate change, accounting for approximately 32% of global energy consumption

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and 34% of global CO_2 emissions [23]. Circular economy principles offer an alternative to the conventional take–make–use–dispose model by maintaining materials at their highest practical value, minimizing waste generation, and reducing dependence on virgin resources [24]. In construction, this transition is achieved through material-efficient design, service-life extension, repair, adaptability, design for disassembly, component reuse, selective deconstruction, and the recycling of construction and demolition waste [25], [26].

Effective circular construction must extend beyond waste recycling and encompass the complete material and building life cycle. Accordingly, circular strategies should be evaluated using material-flow analysis, life-cycle assessment, life-cycle costing, and engineering-performance requirements to prevent environmental burden shifting or the adoption of technically unsuitable recycled materials [26], [27]. Their practical implementation also requires reliable waste separation, consistent material quality, appropriate technical standards, viable secondary-material markets, and collaboration across construction supply chains [28]. Within this framework, processing CW into secondary concrete aggregate provides a direct route for closing material loops, conserving natural sand and gravel, reducing landfill disposal, and improving resource efficiency, provided that the resulting concrete satisfies the required mechanical-performance criteria.

The purpose of this work is to design and implement a quantitative Circular Economy Approaches Model to evaluate the ceramic-waste aggregate concrete, by integrating the consideration of material circularity, mechanical performance, environmental burden and economic feasibility. The proposed framework quantifies ceramic-waste diversion, avoided natural-aggregate consumption, circular material fraction, global-warming potential, embodied energy, aggregate-system cost, and control-normalized strength retention for concrete incorporating CW as fine or coarse aggregate, based on the experimental mixture proportions and the 7- and 28-day mechanical-strength data collected from Radhi

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[29]. The main novelty is the move from conventional evaluations based only on the replacement percentage or single strength properties to a mechanically secured multi-criteria decision framework in which circularity gains are accepted only if essential engineering performance is retained. We propose a single replicable technique that includes mass-balance relationships, cradle-to-gate environmental calculations, economic evaluation, a combined mechanical-performance index, indicator normalization and a Circular Economy Performance Index. It also differentiates between the highest amount of waste included and the most technically balanced combination. This prevents high-circularity mixes with unacceptable strength decreases being recognized as the optimum. The framework offers a transparent basis for selecting ceramic-waste concrete mixtures that balance structural reliability, conservation of virgin resources, landfill diversion, reduction in embodied impacts and production-cost efficiency, using experimentally reported mechanical data together with benchmark-calibrated environmental and economic calculations.

Materials and Methodology

Constituent Materials

Ordinary Portland cement (OPC), manufactured by the Almas Cement Factory, Iraq, was used as the binding material. The cement exhibited initial and final setting times of 123 and 195 min, a Blaine fineness of 315 m²/kg, and compressive strengths of 27.52 and 38.40 MPa at 3 and 7 days, respectively. These properties complied with Iraqi Standard Specification No. 5/1984 [30].

Natural sand with a maximum particle size of 4.75 mm was employed as the fine aggregate. The sand had a specific gravity of 2.64, fineness modulus of 2.70, water absorption of 0.74%, and sulfate content of 0.12%. Semi-crushed natural gravel with a nominal maximum particle size of 10 mm was used as the coarse aggregate. The gravel had a specific gravity of 2.65, water absorption of 0.77%, and sulfate content of 0.08%.

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CW was collected from demolished buildings and ceramic-manufacturing facilities. The material was cleaned to remove visible contaminants and subsequently crushed and sieved into fine- and coarse-aggregate fractions. The ceramic fine aggregate consisted of particles passing the 4.75-mm sieve, whereas the ceramic coarse aggregate consisted of particles passing the 16.5-mm sieve and retained on the 12-mm sieve. Potable water with a pH ranging from 6 to 9 was used in all mixtures.

Experimental Design and Mixture Classification

The experimental dataset employed in the present study was collected from the published article by Radhi [29], which reported the mixture proportions and the 7- and 28-day compressive-, splitting-tensile-, and flexural-strength results of concrete incorporating CW as fine or coarse aggregate. These published experimental observations were adopted as the input dataset for the circular-economy calculations developed in Section 2.4. Accordingly, the present methodological extension evaluates material circularity, avoided natural-aggregate consumption, ceramic-waste diversion, environmental burden, cost, and mechanically safeguarded circular performance using the experimentally reported mixtures and strength results.

The experimental program was designed to investigate the separate effects of replacing natural fine and coarse aggregates with processed CW. Nine concrete mixtures were considered. The reference mixture, designated NA, contained natural sand and gravel without CW. The FA series comprised four mixtures in which CW replaced 25%, 50%, 75%, and 100% of the natural fine aggregate. These mixtures were designated FA1, FA2, FA3, and FA4, respectively. Similarly, the CA series comprised four mixtures incorporating CW as a replacement for 25%, 50%, 75%, and 100% of the natural coarse aggregate and were designated CA1, CA2, CA3, and CA4, respectively.

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Fine- and coarse-aggregate replacement was implemented independently. Ceramic sand was introduced only into the FA mixtures, whereas ceramic gravel was incorporated only into the CA mixtures. This arrangement permitted the effects of ceramic particle size and aggregate function to be evaluated without interference from simultaneous replacement of both aggregate fractions.

The ceramic fine-aggregate content was calculated as:

$$m_{CF} = r_f m_{F0} \qquad (1)$$

and the residual natural fine-aggregate content was:

$$m_F = (1 - r_f) m_{F0} \qquad (2)$$

Similarly, the ceramic coarse-aggregate content was calculated from:

$$m_{CC} = r_c m_{C0} \qquad (3)$$

whereas the remaining natural coarse-aggregate content was:

$$m_C = (1 - r_c) m_{C0} \qquad (4)$$

where m_{CF} and m_{CC} are the ceramic fine- and coarse-aggregate contents (kg/m³), respectively; m_F and m_C are the remaining natural fine- and coarse-aggregate contents (kg/m³); m_{F0} and m_{C0} are the corresponding aggregate contents in the control mixture; and r_f and r_c are the fine- and coarse-aggregate replacement fractions, respectively.

Mixing Proportions

All concrete mixtures were designed using a cement:sand:gravel mass ratio of 1:1.5:2.0. The cement and water contents were maintained at 400 and 140 kg/m³, respectively. The corresponding water-to-cement ratio was:

$$\frac{W}{C} = \frac{140}{400} = 0.35 \qquad (5)$$

The total aggregate content was maintained at 1400 kg/m³. CW replaced the corresponding natural aggregate on an equal-mass basis. Accordingly, the cement content, water content, water-to-cement ratio, and total aggregate mass remained constant across all mixtures. This controlled design enabled the effects of

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aggregate type and ceramic-waste replacement percentage to be evaluated independently. The detailed mixing proportions are presented in Table 1.

Table 1. Mixing proportions of concrete incorporating CW as fine or coarse aggregate.

Mixture	Replacement type	Replacement ratio (%)	Cement (kg/m³)	Natural sand (kg/m³)	Natural gravel (kg/m³)	Ceramic sand (kg/m³)	Ceramic gravel (kg/m³)	Water (kg/m³)
NA	Control	0	400	600	800	0	0	140
FA1	Fine aggregate	25	400	450	800	150	0	140
FA2	Fine aggregate	50	400	300	800	300	0	140
FA3	Fine aggregate	75	400	150	800	450	0	140
FA4	Fine aggregate	100	400	0	800	600	0	140
CA1	Coarse aggregate	25	400	600	600	0	200	140
CA2	Coarse aggregate	50	400	600	400	0	400	140
CA3	Coarse aggregate	75	400	600	200	0	600	140
CA4	Coarse aggregate	100	400	600	0	0	800	140

The replacement percentages in Table 1 refer to the relevant natural-aggregate fraction rather than the total aggregate mass. For example, FA3 incorporated 450 kg/m³ of ceramic sand, corresponding to 75% of the original 600 kg/m³ fine-aggregate content. In contrast, CA3 incorporated 600 kg/m³ of ceramic gravel, representing 75% of the original 800 kg/m³ coarse-aggregate content.

Circular Economy Approaches

A quantitative circular-economy framework was incorporated into the methodology to assess the ability of ceramic-waste concrete to close material loops, reduce the extraction of natural aggregates, divert CW from disposal, and maintain acceptable mechanical performance as shown in Figure 1. The functional unit was defined as **1 m³ of concrete**, while the adopted system boundary extended from ceramic-waste collection and processing to concrete

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production. The boundary included waste collection, cleaning, crushing, grading, transportation, replacement of virgin aggregates, and avoided landfill disposal.

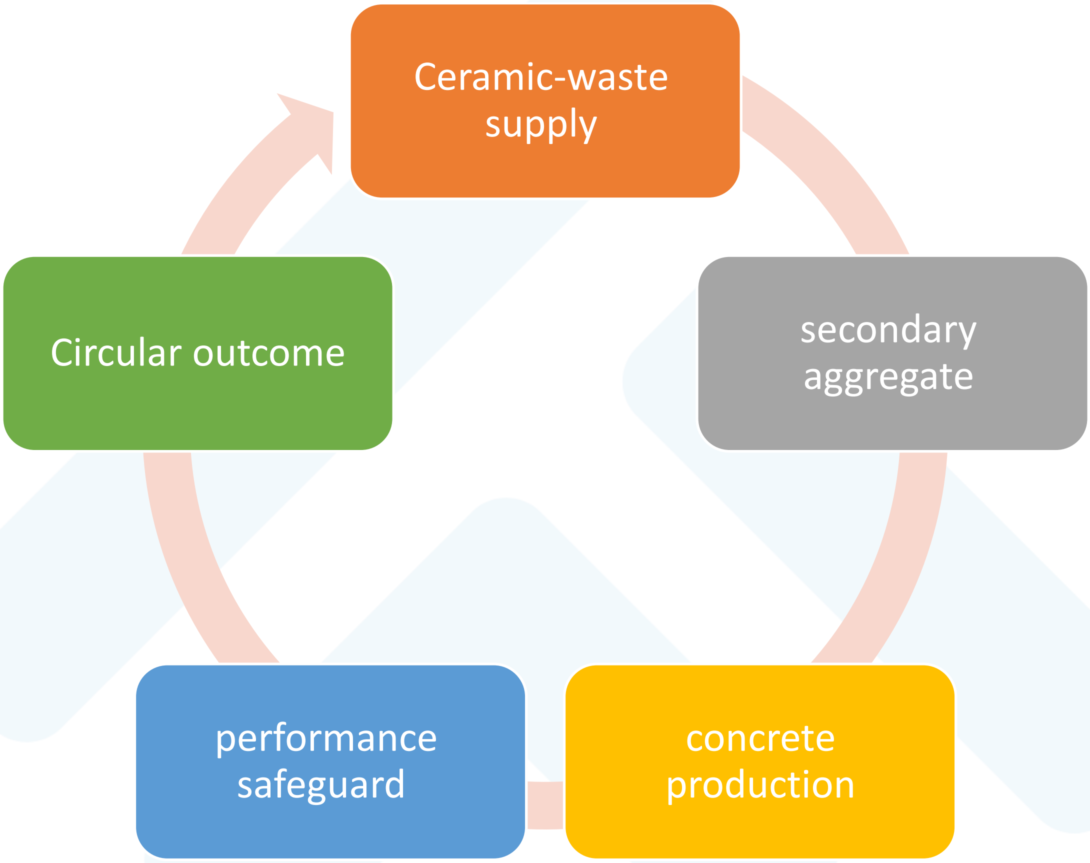

Figure 1. Circular Economy Approaches Model for ceramic-waste aggregate concrete.

The total ceramic-waste content of mixture j was calculated as:

$$m_{CW,j} = m_{CF,j} + m_{CC,j} \qquad (6)$$

where $m_{CW,j}$ is the total ceramic-waste content of mixture j (kg/m^3).

Because CW replaced the corresponding natural aggregate on an equal-mass basis, the mass of avoided natural aggregate was:

$$M_{NA,avoided,j} = m_{CW,j} \qquad (7)$$

The quantity of CW diverted from landfill was calculated as:

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$$M_{CW,diverted,j} = \eta_s m_{CW,j} \qquad (8)$$

where η_s is the usable ceramic-waste yield after cleaning, sorting, crushing, and grading. A value of $\eta_s = 1$ indicates that the entire collected ceramic-waste quantity was suitable for concrete production.

The aggregate circular-material fraction was determined from:

$$CMF_j = \frac{m_{CW,j}}{m_{F,j} + m_{C,j} + m_{CW,j}} \qquad (9)$$

where CMF_j expresses the proportion of the total aggregate mass supplied by CW.

The percentage reduction in natural-aggregate consumption was calculated as:

$$NAR_j = \frac{M_{NA,avoided,j}}{m_{F0} + m_{C0}} \times 100 \qquad (10)$$

For a concrete production volume V, the total natural-aggregate conservation and ceramic-waste diversion were obtained from:

$$Q_{NA,avoided,j} = VM_{NA,avoided,j} \qquad (11)$$

$$Q_{CW,diverted,j} = VM_{CW,diverted,j} \qquad (12)$$

where $Q_{NA,avoided,j}$ and $Q_{CW,diverted,j}$ are expressed in kilograms or tonnes, depending on the adopted project scale.

Environmental Assessment

The cradle-to-gate global-warming potential of each mixture can be determined through material, processing, and transport contributions:

$$GWP_j = \sum_i m_{i,j} \, EF_i^{GWP} + \sum_k m_{k,j} \, d_k EF_k^{tr} + E_j^{proc} EF^{el} - C_{landfill,j}^{avoided} \qquad (13)$$

where $m_{i,j}$ is the mass of material i in mixture j; EF_i^{GWP} is its emission factor; d_k is the transport distance; EF_k^{tr} is the transport emission factor; E_j^{proc} is the electricity consumed during ceramic-waste crushing, sieving, and grading; EF^{el} is the electricity emission factor; and $C_{landfill,j}^{avoided}$ is the justified credit associated with avoided landfill disposal.

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The reduction in global-warming potential relative to the control mixture was calculated as:

$$GWP_{red,j} = \frac{GWP_0 - GWP_j}{GWP_0} \times 100 \qquad (14)$$

The embodied energy of each mixture was estimated from:

$$EE_j = \sum_i m_{i,j}\, CED_i + E_j^{proc} + \sum_k m_{k,j}\, d_k CED_k^{tr} \qquad (15)$$

where CED_i and CED_k^{tr} are the cumulative energy-demand factors associated with material production and transportation, respectively. The corresponding embodied-energy reduction was:

$$EE_{red,j} = \frac{EE_0 - EE_j}{EE_0} \times 100 \qquad (16)$$

The emission and energy factors should be obtained from locally representative environmental product declarations, lifecycle inventory databases, or verified industrial records. Avoided-disposal credits must be applied consistently to prevent double counting.

Economic Assessment

The production cost of each mixture was calculated as:

$$C_j = \sum_i m_{i,j}\, p_i + C_j^{sort} + C_j^{crush} + C_j^{grade} + C_j^{tr} + C_j^{qc} - C_j^{gate} \qquad (17)$$

where p_i is the unit price of material i; C_j^{sort}, C_j^{crush}, and C_j^{grade} are the costs of ceramic-waste processing; C_j^{tr} is the transportation cost; C_j^{qc} is the quality-control cost; and C_j^{gate} represents an avoided landfill charge or waste-supply credit.

Cost saving relative to the control concrete was determined from:

$$C_{save,j} = \frac{C_0 - C_j}{C_0} \times 100 \qquad (18)$$

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Mechanical-Performance Safeguard

Circularity was not evaluated solely according to the quantity of CW incorporated. The selected mixture was also required to maintain adequate mechanical performance. Control-normalized strength-retention ratios were therefore calculated as:

$$SR_{c,j} = \frac{f_{c,j}}{f_{c,0}}, \qquad SR_{t,j} = \frac{f_{t,j}}{f_{t,0}}, \qquad SR_{r,j} = \frac{f_{r,j}}{f_{r,0}} \qquad (19)$$

where $SR_{c,j}$, $SR_{t,j}$, and $SR_{r,j}$ are the compressive-, splitting-tensile-, and flexural-strength retention ratios, respectively.

The three strength indicators were combined into a mechanical-performance index:

$$MPI_j = w_c SR_{c,j} + w_t SR_{t,j} + w_r SR_{r,j} \qquad (20)$$

subject to:

$$w_c + w_t + w_r = 1 \qquad (21)$$

Equal weights of $w_c = w_t = w_r = 1/3$ were adopted for general performance comparison. Different weights may be assigned when a specific mechanical property governs the intended structural application.

Circular Economy Performance Index

To combine indicators expressed in different units, each beneficial indicator was normalized as:

$$N_j^+(x) = \frac{x_j - x_{min}}{x_{max} - x_{min}} \qquad (22)$$

whereas indicators representing environmental burden, cost, or risk were normalized as:

$$N_j^-(x) = \frac{x_{max} - x_j}{x_{max} - x_{min}} \qquad (23)$$

The overall Circular Economy Performance Index was then formulated as:

$$CEPI_j = \omega_1 N(CMF_j) + \omega_2 N(GWP_{red,j}) + \omega_3 N(EE_{red,j})$$

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$$+\omega_4 N(C_{save,j}) + \omega_5 N(MPI_j) - \omega_6 N(Risk_j) \qquad (24)$$

subject to:

$$\sum_{q=1}^{6} \omega_q = 1, \qquad \omega_q \geq 0 \qquad (25)$$

where ω_q denotes the weight assigned to each circular-economy indicator. The preferred mixture was selected by solving:

$$\max_{r_f, r_c} CEPI(r_f, r_c) \qquad (26)$$

subject to:

$$0 \leq r_f, r_c \leq 1 \qquad (27)$$

and the applicable mechanical-performance, workability, material-availability, and transport-distance requirements.

Based on the reported mixture proportions, FA3 incorporated 450 kg/m³ of ceramic sand and consequently avoided an equivalent quantity of natural fine aggregate. Its circular-material fraction was:

$$CMF_{FA3} = \frac{450}{150 + 800 + 450} = 0.3214 = 32.14\% \qquad (28)$$

Therefore, FA3 diverted as much as 450 kg of CW per cubic metre of concrete, reduced virgin fine-aggregate consumption by 75%, and replaced 32.14% of the total aggregate mass with a secondary material. The circular-economy assessment consequently considered FA3 the preferred material-loop configuration when its resource-conservation benefits were evaluated together with its experimentally measured mechanical performance.

Results and Discussion

Data Provenance and Reporting Basis

The experimental data used in the present study were collected from the published article by Radhi [29]. The collected dataset comprises the reported 7- and 28-day compressive, splitting-tensile, and flexural strengths of the control concrete and

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eight concrete mixtures containing CW as fine- or coarse-aggregate replacement. No new mechanical testing was undertaken for the present circular-economy assessment; instead, the published observations were reorganized and interpreted using the material-circularity and mechanical-performance framework established in Section 2.

Table 2 consolidates the mechanical dataset applied in this section. The discussion is intentionally descriptive and mechanistic, without inferential statistical analysis. Replicate-level measurements and measures of dispersion were not available in the source article.

Table 2. Reported mechanical-strength dataset collected from Radhi [29].

Mix	**Replacement**	**Compressive 7 d (MPa)**	**Compressive 28 d (MPa)**	**Splitting tensile 7 d (MPa)**	**Splitting tensile 28 d (MPa)**	**Flexural 7 d (MPa)**	**Flexural 28 d (MPa)**
NA	0%	20.57	33.18	2.54	3.23	3.17	4.03
FA1	25% fine	24.09	36.50	2.75	3.38	3.44	4.23
FA2	50% fine	26.27	37.50	2.87	3.43	3.59	4.29
FA3	75% fine	27.05	39.14	2.91	3.50	3.64	4.38
FA4	100% fine	19.96	37.16	2.50	3.41	3.13	4.27
CA1	25% coarse	22.22	30.18	2.64	3.08	3.30	3.85
CA2	50% coarse	17.20	26.10	2.32	2.86	2.90	3.58
CA3	75% coarse	15.50	23.60	2.20	2.72	2.76	3.40
CA4	100% coarse	10.30	20.00	1.80	2.50	2.25	3.13

Cross-Property Mechanical Performance

The three strength indicators identify FA3 as the mechanically optimum mixture. At both testing ages, FA3 exceeded NA in compression, splitting tension, and flexure, and it also exceeded every other ceramic-waste mixture. The consistent ranking across the three properties reduces the possibility that the selected mixture performs well under only one loading mode. FA1 and FA2 also maintained all reported strengths above the control, whereas FA4 exhibited a small early-age penalty despite its favorable 28-day response.

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The mechanical response therefore exhibits a replacement threshold rather than a monotonic benefit. For ceramic sand, the beneficial packing and interlock effects dominated up to 75% replacement, after which increasing water demand and loss of natural-sand grading balance became more influential. For ceramic gravel, the resource benefit increased with replacement level, but the mechanical penalty grew rapidly beyond 25%. Similar dependence on ceramic source and aggregate condition has been emphasized in prior experimental and review studies [31], [32], [33].

Circular Economy Results

Waste Diversion and Natural-Aggregate Conservation

The direct circular-economy results calculated from the mixture mass balance are summarized in Table 3 and Figure 2. Because every mixture contained 1400 kg/m³ of total aggregate, the ceramic-waste mass introduced was equal to the mass of virgin aggregate avoided. The fine-aggregate series diverted from 150 to 600 kg/m³ of CW, whereas the coarse-aggregate series diverted from 200 to 800 kg/m³. At a production scale of 1000 m³, these quantities correspond to 150-600 tonnes and 200-800 tonnes of CW, respectively.

Table 3. Direct circular-resource indicators calculated from the reported mixture proportions.

Mix	CW stream	CW diverted (kg/m³)	Natural aggregate avoided (kg/m³)	Target constituent reduction (%)	Circular material fraction (%)
NA	None	0	0	0	0.00
FA1	Ceramic sand	150	150	25	10.71
FA2	Ceramic sand	300	300	50	21.43
FA3	Ceramic sand	450	450	75	32.14
FA4	Ceramic sand	600	600	100	42.86
CA1	Ceramic gravel	200	200	25	14.29
CA2	Ceramic gravel	400	400	50	28.57
CA3	Ceramic gravel	600	600	75	42.86
CA4	Ceramic gravel	800	800	100	57.14

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FA3 diverted 450 kg/m³ of CW, avoided the same mass of natural sand, reduced virgin fine-aggregate demand by 75%, and achieved a circular material fraction of 32.14%. FA4 increased the circular material fraction to 42.86%, while CA4 reached the maximum value of 57.14%. These higher mass-based circularity values cannot, however, be interpreted independently of mechanical performance. The comparison demonstrates why waste incorporation alone is an insufficient optimization criterion.

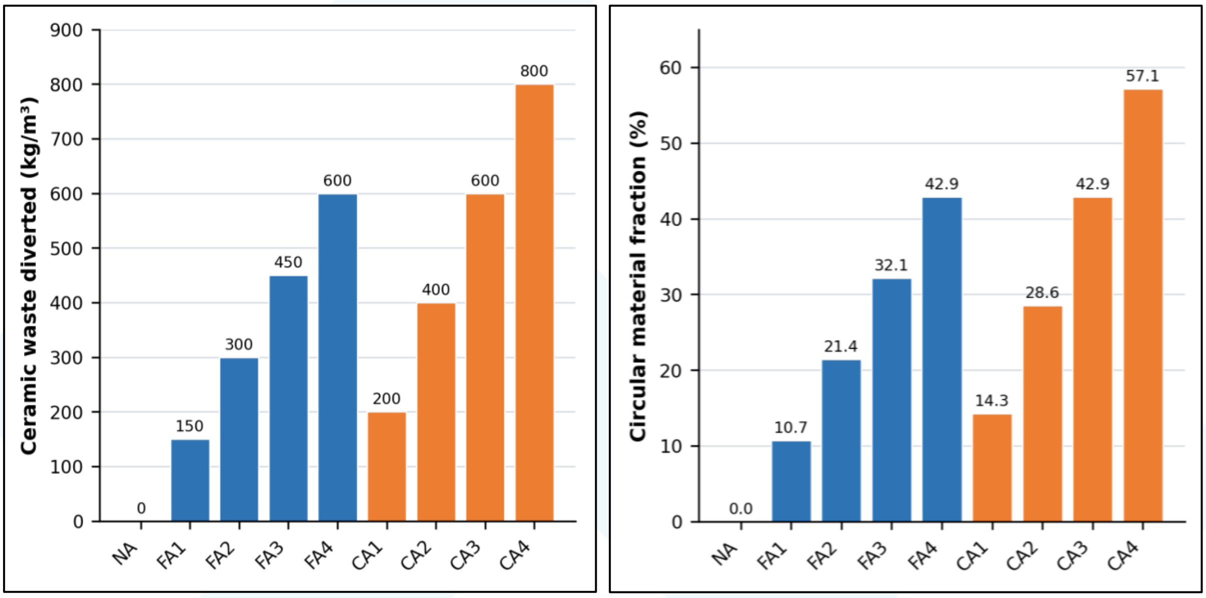

Figure 2. Ceramic-waste diversion and circular material fraction obtained from the reported mixture mass balance.

Mechanical-Performance Safeguard

Table 4 applies the control-normalized strength-retention ratios and the equal-weight mechanical performance index defined in Section 2. The 28-day MPI increased from 1.000 for NA to 1.117 for FA3, confirming that FA3 provided the strongest combined compressive, splitting-tensile, and flexural response. FA4 maintained an MPI of 1.079 at 28 days, but its minimum retention ratio across

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both ages and all three properties was 0.970 because its 7-day compressive strength fell below the control.

Table 4. Mechanical-performance safeguard and circularity screening results.

Mix	SRc, 28 d	SRt, 28 d	SRr, 28 d	MPI, 28 d	Minimum SR, 7-28 d	CMF (%)	Safeguard outcome
NA	1.000	1.000	1.000	1.000	1.000	0.00	Baseline
FA1	1.100	1.049	1.049	1.066	1.049	10.71	Pass
FA2	1.130	1.063	1.063	1.085	1.063	21.43	Pass
FA3	1.180	1.086	1.086	1.117	1.086	32.14	Pass
FA4	1.120	1.058	1.058	1.079	0.970	42.86	Does not pass
CA1	0.910	0.954	0.954	0.939	0.910	14.29	Does not pass
CA2	0.787	0.887	0.887	0.853	0.787	28.57	Does not pass
CA3	0.711	0.843	0.843	0.799	0.711	42.86	Does not pass
CA4	0.603	0.776	0.776	0.719	0.501	57.14	Does not pass

Note: The conservative safeguard requires every compressive, splitting-tensile, and flexural strength-retention ratio at both 7 and 28 days to be at least 1.00 relative to NA.

Under this conservative requirement, FA1, FA2, and FA3 passed the mechanical safeguard, while FA4 and all ceramic-gravel mixtures did not. Among the passing alternatives, FA3 achieved the greatest waste diversion and circular material fraction.

Environmental and Economic Assessment Results

A numerical environmental and economic scenario was calculated for the 1 m³ functional unit using the mixture-specific circular material fraction and the Iraqi ceramic-waste concrete benchmarks reported by Radhi [29]. The benchmark study reported a global-warming potential (GWP) of 295 kg CO2-eq/m³ and cumulative energy demand of 3200 MJ/m³ for conventional concrete, compared with ranges of 215–245 kg CO2-eq/m³ and 2400–2800 MJ/m³ for concrete containing 30–50% CW. The midpoint values, 230 kg CO2-eq/m³ and 2600 MJ/m³, were adopted at a benchmark ceramic fraction of 0.40. Its published aggregate-system cost comparison, USD 26.00/m³ for conventional aggregate

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and USD 13.50/m³ for the ceramic alternative, was adopted for the economic calculation. Table 5 records every numerical input so that the calculation is reproducible.

Table 5. Adopted benchmark parameters for the numerical environmental and economic assessment.

Indicator	Control benchmark ($x = 0$)	Ceramic benchmark ($x_{40} = 0.40$)	Unit	Adopted basis
Global-warming potential	295	230	kg CO2-eq/m³	Midpoint of the reported 215–245 kg CO2-eq/m³ range
Embodied energy / CED	3200	2600	MJ/m³	Midpoint of the reported 2400–2800 MJ/m³ range
Aggregate-system cost	26.00	13.50	USD/m³	Aggregate purchase, transport, processing, and avoided disposal

Note: CED = cumulative energy demand.

$$Y_j = Y_0 - [(Y_0 - Y_{40}) / 0.40]x_j \qquad (27)$$

In Equation (27), Y represents GWP, embodied energy, or aggregate-system cost; Y_0 is the control benchmark; Y_{40} is the adopted benchmark at a ceramic fraction of 0.40; and x_j is the circular material fraction of mixture j. The resulting percentage changes were calculated as GWP reduction = $[(GWP_0 - GWP_j)/GWP_0] \times 100$, embodied-energy reduction = $[(EE_0 - EE_j)/EE_0] \times 100$, and cost saving = $[(C_0 - C_j)/C_0] \times 100$, consistent with Equations (14), (16), and (18) in Section 2.

For example, FA3 contained 450 kg/m³ of CW within 1400 kg/m³ total aggregate, so x(FA3) = 450/1400 = 0.3214. Therefore, GWP(FA3) = 295 − [(295 − 230)/0.40](0.3214) = 242.77 kg CO2-eq/m³; EE(FA3) = 3200 − [(3200 − 2600)/0.40](0.3214) = 2717.86 MJ/m³; and C(FA3) = 26.00 − [(26.00 − 13.50)/0.40](0.3214) = USD 15.96/m³. Relative to NA, these values represent reductions of 17.71% in GWP, 15.07% in embodied energy, and 38.63% in aggregate-system cost.

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Table 6. Calculated environmental and aggregate-system economic results for the 1 m³ functional unit.

Mix	CMF (%)	GWP (kg CO2-eq/m³)	GWP reduction (%)	Embodied energy (MJ/m³)	EE reduction (%)	Aggregate-system cost (USD/m³)	Cost saving (%)
NA	0.00	295.00	0.00	3200.0	0.00	26.00	0.00
FA1	10.71	277.59	5.90	3039.3	5.02	22.65	12.88
FA2	21.43	260.18	11.80	2878.6	10.04	19.30	25.76
FA3	32.14	242.77	17.71	2717.9	15.07	15.96	38.63
FA4	42.86	225.36	23.61	2557.1	20.09	12.61	51.51
CA1	14.29	271.79	7.87	2985.7	6.70	21.54	17.17
CA2	28.57	248.57	15.74	2771.4	13.39	17.07	34.34
CA3	42.86	225.36	23.61	2557.1	20.09	12.61	51.51
CA4	57.14	202.14	31.48	2342.9	26.79	8.14	68.68

The calculated results show a monotonic reduction in GWP, embodied energy, and aggregate-system cost as the ceramic fraction increased. CA4 produced the largest numerical reductions (31.48% GWP, 26.79% embodied energy, and 68.68% aggregate-system cost), but it did not pass the mechanical safeguard and its values require extrapolation beyond the benchmark range. Among the safeguard-compliant mixtures, FA3 delivered the strongest sustainability outcome: it reduced estimated GWP by 52.23 kg CO2-eq/m³, embodied energy by 482.1 MJ/m³, and aggregate-system cost by USD 10.04/m³, while retaining the highest 28-day mechanical performance index. FA3 is therefore the preferred environmental, economic, and mechanical compromise within the evaluated matrix.

Conclusion

This study developed a mechanically safeguarded circular-economy framework for ceramic-waste aggregate concrete. The results demonstrate that the type and proportion of ceramic aggregate significantly influence the balance between circularity and engineering performance; therefore, the mixture containing the highest recycled content cannot automatically be considered the optimum solution.

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Ceramic sand provided a substantially more favorable mechanical response than ceramic gravel. FA3, containing 75% fine-aggregate replacement, achieved the best overall performance, with 28-day compressive, splitting-tensile, and flexural strengths of 39.14, 3.50, and 4.38 MPa, respectively, and the highest mechanical-performance index of 1.117. FA1, FA2, and FA3 satisfied the conservative mechanical safeguard across all evaluated properties and testing ages. Conversely, FA4 failed because its minimum strength-retention ratio decreased to 0.970 at 7 days. All ceramic-gravel mixtures failed the safeguard, with CA4 recording a 28-day mechanical-performance index of 0.719 and a minimum strength-retention ratio of 0.501. These findings indicate that increasing ceramic-gravel replacement produces substantial mechanical penalties, whereas ceramic-sand replacement remains technically advantageous up to 75%.

From a resource-circularity perspective, FA3 diverted 450 kg/m³ of CW from disposal, avoided an equivalent quantity of natural sand, reduced virgin fine-aggregate demand by 75%, and achieved a circular material fraction of 32.14%. The benchmark-calibrated assessment estimated a global-warming potential of 242.77 kg CO_2-eq/m³, embodied energy of 2717.9 MJ/m³, and aggregate-system cost of USD 15.96/m³ for FA3. Relative to the control mixture, these values correspond to reductions of 52.23 kg CO_2-eq/m³ (17.71%), 482.1 MJ/m³ (15.07%), and USD 10.04/m³ (38.63%), respectively. Although CA4 achieved the highest circular material fraction of 57.14% and the largest calculated environmental and economic reductions, it failed the mechanical safeguard, while its impact values required extrapolation beyond the adopted benchmark range. Consequently, CA4 cannot be regarded as a technically acceptable optimum.

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