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The Effect of Utilizing Concrete Waste as Coarse and Fine Aggregate on the Concrete Properties

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ABSTRACT

This study investigates the technical and economic feasibility of utilizing recycled concrete aggregate (RCA), derived from waste concrete cubes, as a substitute for natural coarse and fine aggregates in structural concrete. Five concrete mixes were designed with RCA replacement levels of 0%, 25%, 50%, 75%, and 100% by weight. The experimental program followed a fixed mix proportion of 1:1.5:3 (cement:sand: coarse aggregate) with a water-to-cement ratio adjusted to maintain a constant slump of 45 mm. Fresh properties were evaluated through slump and compaction factor tests, while hardened properties were assessed using compressive and tensile strength tests at 7 and 28 days. RCA was prepared by crushing laboratory-tested concrete cubes to meet grading standards for both fine and coarse fractions. Results demonstrated that mixes incorporating RCA required increased water content to maintain workability. The mix with 25% RCA substitution exhibited optimal performance, achieving 96% compaction, 94% of the reference compressive strength, and 79% of the reference tensile strength at 28 days. Additionally, a quantitative economic assessment revealed a cost reduction of \$1.56/m³ at this substitution level. These findings confirm that the partial replacement of natural aggregates with RCA offers a technically sound, economically viable, and environmentally sustainable solution for concrete production, particularly in regions burdened with high volumes of construction waste.

1. INTRODUCTION

For a typical concrete mix, approximately 34% by weight of the mix is sand, and the crushed stone accounts for about 48% by weight. Therefore, aggregate consumption in concrete mixes is the main and huge relative to other human activities [1, 2]. Today, the world is moving towards a green solution to reduce pollution and conserve natural resources; green concrete is one of these solutions. There are many modern ways to manufacture environmentally friendly concrete (green concrete), such as fly ash [3-5], fly ash aggregate, plastic waste, and recycled concrete [6-8]. Recycled concrete is crushed concrete in a specific grade used as an aggregate in a new mix of concrete. Such a solution is an environmentally friendly solution because waste is used to replace a natural resource [9].

Concrete is a favorable construction material; nonetheless, the globe is confronted with a significant challenge in managing concrete waste due to its durability, heaviness, and large volumes. In Iraq, building trash is indiscriminately discarded along roadsides and neglected in yards due to the absence of a controlled disposal system. According to Hassan [10], the amount of building trash generated by Iraqi cities is estimated to be 1,111,788 tons per year. The escalating volumes of construction waste in Iraq may be attributed to the devastation caused by wars and conflicts, resulting in the complete demolition of whole cities [11]. Additionally, the accumulation of construction trash is also a consequence of deteriorated old structures that have exceeded their intended lifespan [12].

Furthermore, the inadequate availability of appropriate landfills for the disposal of construction waste exacerbates the problem [13]. Furthermore, the government is compelled to develop new building complexes at an accelerated rate due to the substantial population growth, necessitating the use of excessive quantities of concrete. Moreover, the rise in concrete production is directly correlated with the growth in the exploitation of natural aggregate resources. Hence, the exploitation of concrete debris is essential as a method of recycling. This study aims to investigate the viability of using waste concrete as coarse aggregate at various replacement levels to determine the feasibility of incorporating Iraqi waste concrete into the production of environmentally friendly concrete.

The properties and performance of recycled concrete aggregate (RCA) in concrete have been extensively studied, particularly in the context of sustainability-driven construction practices [14]. RCA, by its very nature, comprises both residual natural aggregate and remnants of cementitious mortar from the original concrete matrix. This composite structure results in increased porosity, elevated water absorption capacity, and a comparatively rough surface texture, all of which influence the rheological and mechanical characteristics of fresh and hardened concrete [14]. While RCA incorporation tends to reduce compressive and tensile strength due to weakened interfacial transition zones (ITZ) and residual microcracks, proper proportioning and quality control can yield satisfactory performance levels [15-17].

Malešev et al. [18] evaluated the workability of concrete mixes containing RCA at replacement levels of 0%, 50%, and 100% by weight of natural coarse aggregate. Workability was tested via a slump test at different time intervals, both during mixing and after 30 minutes of mixing. They found that workability reduces with increasing RCA content. In addition, slump readings reduced after 30 minutes but were on par with previous readings.

Saleh Lamein [19] employed a constant water-to-cement ratio of 0.54 and investigated different replacement levels of 0, 35, 50, and 100% of recycled concrete aggregate (RCA) by weight of natural coarse aggregate in the concrete mix. The results indicated that slump values decreased with the incorporation of RCA. Similar observations were reported by Qasrawi et al. [20], noted that increasing the RCA content is inversely proportional to slump readings.

The compressive strength of RCA concrete mixes will depend on several factors. These factors include the use of concrete as aggregate, the mix ratio, the quality of curing, and the additives used. However, as a rule, concrete mixes tend to exhibit lower compressive strengths when containing RCA content compared to those of concrete with natural coarse aggregate. Therefore, an ideal replacement level should be carefully selected to achieve the required compressive strength. However, other studies indicate that the presence of RCA has a positive impact on compressive strength. According to Levy and Helène [21], replacing 20% of natural coarse aggregate or ancient masonry with RCA by weight is anticipated to result in similar or even improved behavior compared to the reference concrete created with natural aggregates, in relation to the parameters examined in this study. This fact supports the rationale for using these specific types of concrete, as they have the potential to aid in environmental conservation while achieving comparable performance to regular concrete at lower costs. Malešev et al. [18] stated that completely replacing the natural coarse aggregate with RCA in concrete achieved nearly double the compressive strength at 28 days of that of the reference concrete mix.

Tensile strengths are inversely proportional to RCA content. However, a study showed that when using a W/C ratio of 0.65 with a replacement level of 25% of RCA, the tensile strength was higher than that of the reference mix [22]. Another study conducted by Thomas et al. [23] showed that replacing natural coarse aggregate with RCA entirely reduced the tensile strength by 20% compared to the control mix. Other studies reported a reduction in tensile strength of 21% and 35%.

Catastrophic events, such as earthquakes, inundations, and avalanches, cause extensive destruction to many structures [24]. Furthermore, human-induced catastrophes such as armed conflicts may lead to a substantial accumulation of building waste and rubble [25]. The destruction of infrastructure components will further worsen the situation. The demolition of structures, regardless of the cause, would have comparable consequences [26]. The process of rebuilding these structures is costly and will have adverse environmental consequences. The annual worldwide output of concrete in our rapidly expanding industrialized world is approximately 6 billion tons, leading to adverse environmental consequences [27]. Obtaining enormous amounts of aggregate, whether natural or crushed, from land will have a detrimental effect on the ecosystem. Dismantling concrete buildings and disposing of the resulting concrete debris would further exacerbate the issue [28]. Therefore, the act of recycling construction materials plays a pivotal role in conserving natural resources and fostering sustainable development by safeguarding these resources. Therefore, it decreases the amount of demolition trash generated from structures that have been destroyed [29]. Therefore, the process of recycling concrete debris is crucial for disposing of accumulated destroyed concrete over a period. For instance, the yearly quantity of structures destroyed in Europe totals around 300 million tons [30]; however, in the Middle East, this quantity more than doubles owing to the conflicts in Gaza, Yemen, Syria, and Iraq [31]. Many researchers have used recycled concrete aggregate as a subject for their research. In general, they recommended an optimum replacement of 25% RCA to give better results. In addition, various factors influence the properties of concrete containing RCA, such as the water-to-cement (W/C) ratio and additives, which may yield better results.

While numerous studies have investigated the mechanical behavior of RCA-based concrete, notable limitations persist in the current literature. Most research, including the present study, focuses predominantly on short-term mechanical performance, often neglecting long-term durability aspects such as freeze-thaw resistance, shrinkage, creep, and chloride ion penetration. Furthermore, variations in RCA source quality are not always rigorously characterized, which may affect the generalizability of the findings. The absence of comprehensive life cycle assessment (LCA) frameworks in many studies limits the understanding of the broader environmental impact of RCA. Additionally, discrepancies between laboratory-scale performance and real-world field conditions remain a critical research gap. Addressing these limitations is essential to establishing robust guidelines for RCA application in structural concrete.

The selection of laboratory-tested concrete cubes as the source material for RCA production offers significant advantages over demolition waste and other heterogeneous sources. Laboratory waste cubes are characterized by controlled mix proportions, known mechanical properties, and a standardized curing regime, which collectively ensure homogeneity in the resulting recycled aggregate. Moreover, such cubes are free from deleterious materials commonly found in demolition waste, such as gypsum, bricks, wood fragments, and reinforcing steel, thereby minimizing contamination risks. This controlled source facilitates accurate prediction of the mechanical performance of RCA-incorporated concrete. However, this approach is not without limitations. The volume of waste cubes available may be insufficient for large-scale applications, and additional crushing and grading processes are required to produce aggregates that conform to standard specifications. Nonetheless, the use of such well-characterized RCA enhances experimental reproducibility and enables more reliable interpretation of concrete behavior.

This research aims to comprehensively assess the structural performance, environmental impact, and economic feasibility of incorporating recycled concrete aggregate (RCA) as a partial or complete replacement for both natural coarse and fine aggregates in conventional concrete. The novelty of the study lies in its integrated experimental–economic framework that evaluates dual aggregate replacement levels (0–100%) using RCA produced from standardized waste concrete cubes. The methodology involved the preparation of ten concrete mixes—five for coarse aggregate replacement (C0–C100) and five for fine aggregate replacement (S0–S100)—using a consistent mix ratio of 1:1.5:3 with variable water content to sustain uniform workability. Mechanical properties were examined through compressive and tensile strength testing, while workability was evaluated using slump and compaction factor tests. A cost evaluation was also performed based on typical aggregate pricing in Iraq, demonstrating that 25% RCA replacement reduces material cost by \$1.56/m³ without compromising structural integrity. This study makes a significant contribution to the advancement of sustainable construction practices by validating the applicability of RCA through a combination of laboratory testing and life-cycle-informed economic modeling.

2. MATERIALS AND METHODOLOGY

2.1 Materials

The materials utilized in this study include cement, sand, normal coarse aggregate, waste concrete, and water.

2.1.1 Cement

The type of cement used in the mix was Sulphate Resistant Portland Cement (SRPC), available in a 50kg pack under the trade name Aljesser. Table 1 lists the physical and chemical properties of the cement.

Table 1. Physical and chemical features

Physical Features	
Compressive strength in 3 days (MPa)	18.41
Compressive strength in 7 days (MPa)	27.60
Smoothness (%)	96.00
Initial setting time (min)	85
Final setting time (hrs)	4.43
Chemical features	
SiO_2	20.17%
CaO	60.91%
MgO	1.37%
Fe_2O_3	5.28%
Al_2O_3	4.23%
SO_3	2.20%
C_3A	2.28%
L.O.I	2.28%
Insoluble Materials	1.07%

2.1.2 Sand

The sand used in the mixes prepared for this research is normal, washed fine aggregate commonly used in concrete production. The sand utilized is within these grades as shown in Table 2. The determination of soluble sulfate content (SO_3) in the sand and coarse aggregates was carried out according to standard procedures outlined in ASTM C114. The sand has a percentage of soluble salts (SO_3) of 0.37.

Table 2. Sand's sieve analysis

No. of Sieve	Retained Mass (g)	Retained (%)	Passing (%)	Cumulative (%)
10	0	0	100	100
4.75	17	1.42	100-90	98.58
2.36	186	15.5	75-100	84.5
1.18	335	27.92	55-90	72.08
600	758	63.17	35-59	36.83
300	1081	90.08	8-30	9.92
150	1096	91.33	0-10	8.67
Pan	1156	96.33	5	3.67

2.1.3 Normal coarse aggregate

The following grades of normal coarse aggregate utilized in the study are shown in Table 3. The coarse aggregate contains soluble salts at a concentration of 0.12.

Table 3. Natural coarse aggregate's sieve analysis

Sieve Size (mm)	Retained Mass (gm)	Retained (%)	Passing (%)	Cumulative (%)
37.5	0	0	100	**100**
20	73	1.46	98.54	**100-95**
10	2726	54.52	45.48	**60-30**
5	4902	98.04	1.96	**0-10**
Pan	4993	99.86	0.14	**3**

2.1.4 Waste concrete as coarse and fine aggregate

Figure 1. Transition of the cubes to RCA

The recycled concrete aggregate (RCA) used in this study was obtained through a systematic mechanical crushing process applied to standardized 150×150×150 mm concrete cubes previously cast with a nominal mix proportion of 1:1.5:3, exhibiting characteristic compressive strengths ranging from 20 to 26 MPa. The fragmentation process was initiated using a laboratory-grade jaw crusher to achieve primary disintegration of the cube specimens, as shown in Figure 1. Subsequently, the crushed material underwent a rigorous sieving procedure, in accordance with ASTM C136, to classify the aggregates into coarse (5–20 mm) and fine (<4.75 mm) fractions consistent with conventional aggregate grading envelopes. A manual inspection was conducted after sieving to eliminate oversized or irregular particles and ensure adherence to standard granulometric requirements. This controlled processing approach enabled the production of RCA with particle size distributions similar to those of natural aggregates, thereby facilitating a reliable evaluation of its influence on concrete rheology and mechanical performance under equivalent mix design conditions.

2.1.5 Water

Faucet water is utilized in all concrete mixes in this study.

2.2 Mixing design and procedure

The normal coarse and fine aggregate utilized in this study is replaced at different replacement levels. The replacement levels are 0%, 25%, 50%, 75%, and 100% by weight of coarse and fine aggregate, respectively (C0, C25, C50, C75, and C100) and (S0, S25, S50, S75, and S100). The mix ratio for the mixes is taken as 1 cement: 1.5 sand: 3.0 coarse aggregate. The W/C ratio is taken as 0.45. Tables 4 and 5 list the mix design for each concrete mix.

Table 4. Mix design for the prepared mixes

Mix	Cement (kg/m^3)	Sand (kg/m^3)	Aggregate (kg/m^3)	RCA (kg/m^3)	W/C
C0	410	640	1250	0	**0.45**
C25	410	640	937.5	312.5	**0.45**
C50	410	640	625	625	**0.45**
C75	410	640	312.5	937.5	**0.45**
C100	410	640	0	1250	**0.45**

Table 5. Mix design for the prepared mixes

Mix	Cement (kg/m^3)	Sand (kg/m^3)	Aggregate (kg/m^3)	RCA (kg/m^3)	W/C
S0	410	640	1250	0	**0.45**
S25	410	480	1250	160	**0.45**
S50	410	320	1250	320	**0.45**
S75	410	160	1250	480	**0.45**
S100	410	0	1250	640	**0.45**

Figure 2. The mixing procedure followed in the research

Regarding the mixing procedure, the same method is used for all concrete mixes. The first step is to mix the sand, coarse aggregate (normal or recycled), and cement together. The water is then added gradually to the dry mix until the required workability is achieved. The fresh mix is then distributed on cube and cylinder samples to be tested afterward. The concrete samples were cured by using the sealed curing method [32]. In which the samples are sprayed with water and then wrapped using plastic film until the testing date. Figure 2 illustrates the mixing procedure utilized throughout the research.

2.3 Testing program

Concrete mixes containing RCA are assessed by testing their fresh and hardened state features. Slump and compaction test readings were used to assess the fresh state features of the concrete. Hardened state features were assessed by testing the compressive strength, tensile strength, and ultrasonic pulse velocity.

2.3.1 Workability

The workability tests utilized for fresh concrete in this research are:

Slump test: The concrete slump test is a field test utilized to assess the consistency and workability of freshly mixed concrete. This test is crucial in guaranteeing the prompt and tangible quality of concrete [33]. Figure 3 displays the slump cone.

Figure 3. Slump cone apparatus

Compaction factor: The compaction factor is a laboratory test utilized to measure the workability of concrete. The compaction factor refers to the ratio between the weights of concrete that is partly compressed and concrete that is completely compacted.

2.3.2 Compressive strength

150×150×150 mm cubes are utilized for assessing compressive strength [34]. Each test involves the use of three cubes, and the average of these cubes is recorded as a single age reading. The compressive strength is evaluated at the ages of 7 and 28 days.

2.3.3 Tensile strength

To assess tensile strength, cylinders with a diameter of 100mm and a height of 200mm are utilized in this experiment [35]. Three cylinders represent each age, and the average of these cylinders is utilized as the reading for that specific age. The tensile strength is assessed at the ages of 7 and 28 days.

3. RESULTS AND ANALYSIS

The results obtained from the testing program conducted on the prepared samples are listed below. Additionally, an analysis of the results will be presented, highlighting the relationships between the tested parameters.

3.1 Slump and compaction factor

Tables 6 and 7 list the results of the slump and compaction factor for the prepared mixes. The slump reading was fixed at 45mm for all the mixes regardless of RCA content.

Table 6. Slump, W/C ratio, and compaction factor readings for the mixes

Mix	Slump Reading (mm)	Compaction Factor (%)	W/C
C0	45	93	0.45
C25	45	96	0.50
C50	45	95	0.50
C75	45	95	0.51
C100	45	93	0.52

Table 7. Slump, W/C ratio, and compaction factor readings for the mixes

Mix	Slump Reading (mm)	Compaction Factor (%)	W/C
S0	45	93	0.45
S25	45	96	0.50
S50	45	96	0.50
S75	45	95	0.52
S100	45	94	0.53

Results show that to maintain a fixed slump reading of 45mm, the water-to-cement (W/C) ratio had to be increased for mixes containing RCA content. Mixes containing RCA required more water compared to the reference mix C0 and S0. An increase in RCA content caused an increase in water demand.

Compaction factor readings had no definitive trend when comparing the results between the prepared mixes. The highest compaction factor reading was exhibited by Mix C25, which contained 25% by weight of natural aggregate RCA, at 96%.

3.2 Compressive strength

Compressive strength findings are listed in Figures 4 and 5. Results show that the compressive strength decreases with the presence of RCA content in the mix. However, the different RCA content showed an unpredictable trend. The C25 and S25 mix exhibited the highest strength value compared to those shown by C25 and C100. Additionally, the S25 mix exhibited the highest strength value compared to the C25 mix.

The compressive strength of C25 and S25 can be related to the compaction factor reading stated before, which was the highest among the mixes containing RCA content. The replacement of 25% by weight of natural coarse and fine aggregate with RCA can be considered the optimum in terms of compressive strength, achieving a strength of 94% that of the reference mix R0. Mix C100 exhibited a compressive strength of 32.87 MPa at 28 days, which is 77% of that of C0, and mix S100 exhibited a compressive strength of 28.74 MPa at 28 days, which is 67% of that of the reference mix. The lowest strength was exhibited by mix C100 and S100, which achieved readings of 32.87 MPa and 28.74 MPa, respectively. However, compressive strength readings increased with age regardless of RCA content. This increase in compressive strength suggests that the samples are densifying with age; hence, the hydration process is contributing to the reduction of pores within the paste.

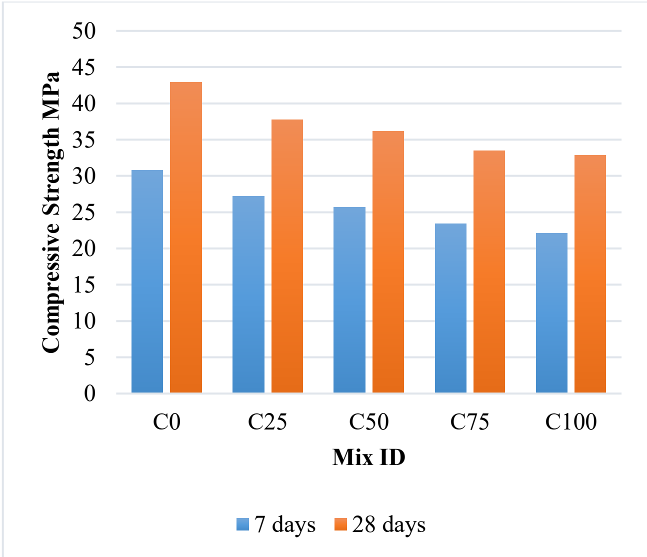

Figure 4. The compressive strength of the coarse aggregate replacement mixture

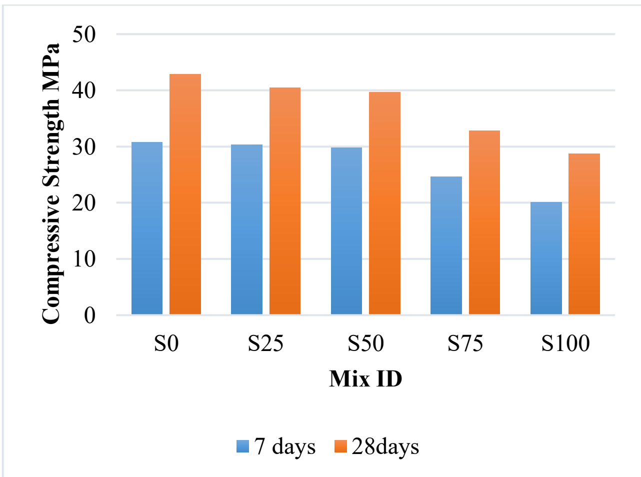

Figure 5. The compressive strength of the sand replacement mixture

When using RCA as a coarse and fine aggregate, the cubes' sample weight for both was reduced due to blocking most of the aggregate porosity in the previous cement mortar, as shown in Figures 6 and 7. The compressive strength readings can be linked to the weight of the tested cubes. Figures 8 and 9 list the weights of the cubes at the same ages and for all mixes.

The nearest weights to those shown by the reference mix are exhibited by mix C25. This mix is slightly denser than the other mixes containing RCA content. The hydration process in this mix is more efficient than that in the other mixes containing RCA content.

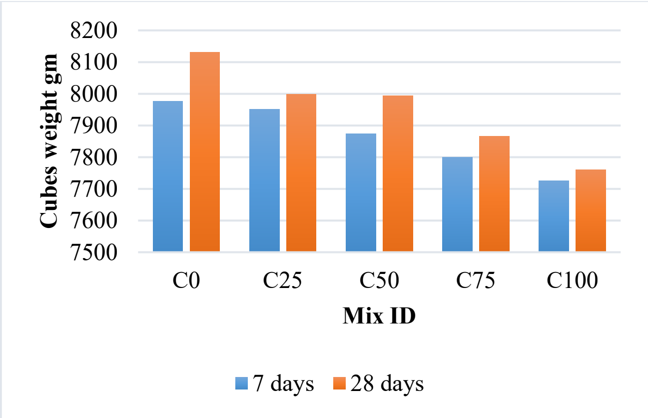

Figure 6. The cube's weight of the coarse aggregate replacement mixture

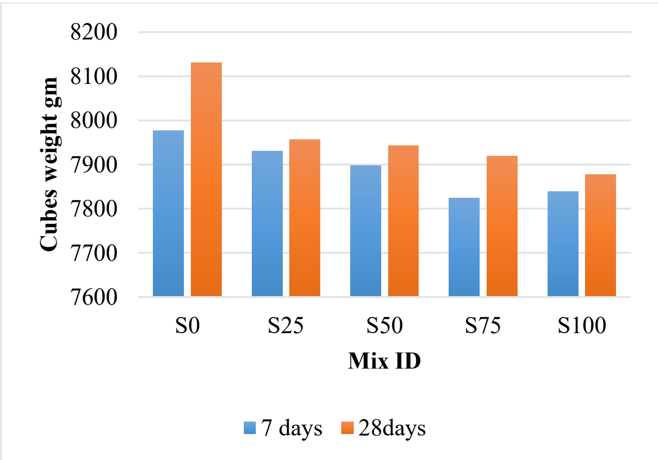

Figure 7. The cube's weight of the sand replacement mixture

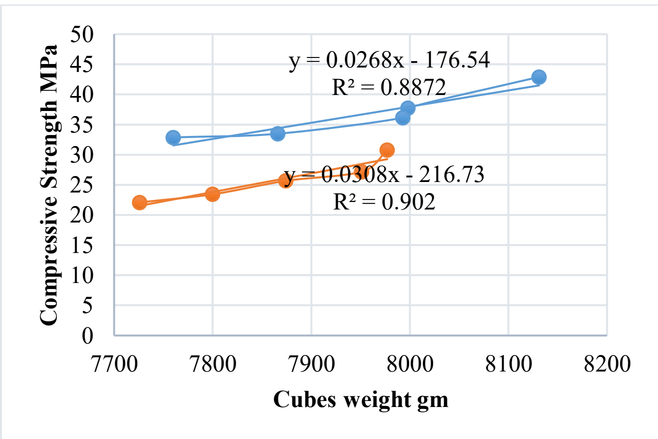

Figure 8. The relationship between compressive strength and the weight of the cubes of the coarse aggregate replacement mixture

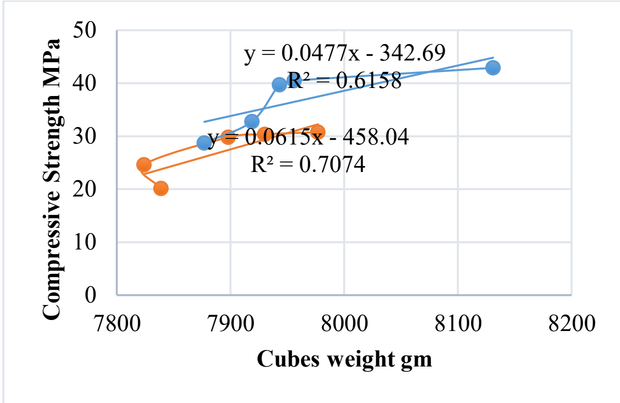

Figure 9. The relationship between compressive strength and the weight of the cubes of the sand replacement mixture

3.3 Tensile strength

The results of the tensile strength test are illustrated in Figures 10 and 11. The results show that the mixes have followed a similar trend to that of the compressive strength. The mix C25 and S25 showed the highest tensile strength compared to those obtained by the mixes with RCA content. The tensile strength of C25 at the age of 28 days was 79% of that exhibited by the reference mix at the same age. The second-highest is the tensile strength shown by C50, followed by the lowest tensile strength shown by C100.

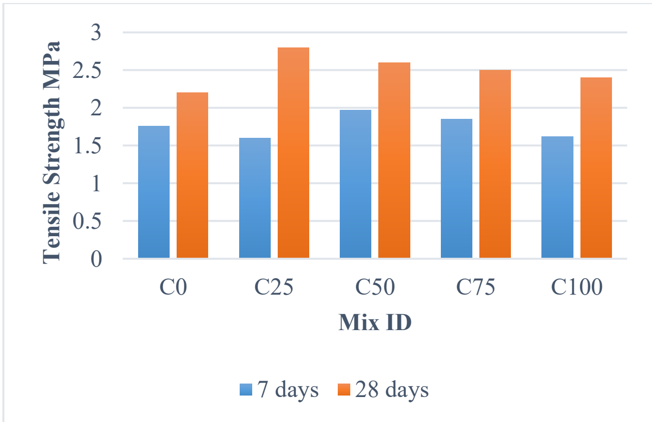

Figure 10. The tensile strength of the coarse aggregates' replacement mixture

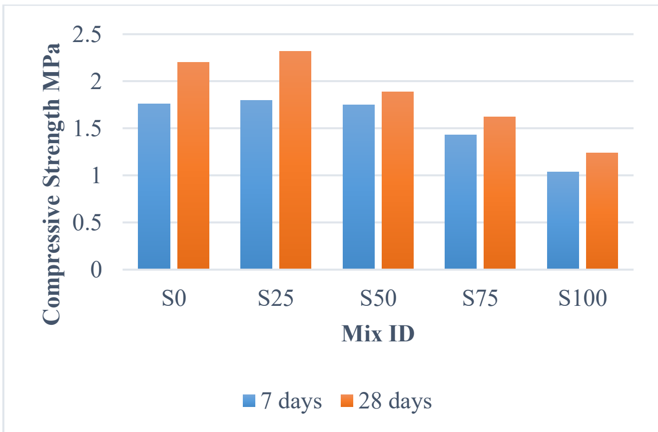

Figure 11. The tensile strength of the sand replacement mixture

4. ECONOMIC FEASIBILITY OF USING RECYCLED CONCRETE AGGREGATE (RCA)

A comprehensive economic feasibility analysis of recycled concrete aggregate (RCA) in concrete mixtures must account for material acquisition, processing, transportation, and waste management costs, in comparison with conventional concrete using natural aggregates [36]. In this study, the RCA was sourced from local concrete waste (e.g., rejected test cubes), significantly minimizing raw material costs. Based on average regional data, the cost of natural coarse aggregate in Iraq is approximately \$10–\$15 per ton. In contrast, RCA derived from on-site crushing operations can be produced at \$6–\$8 per ton, inclusive of crushing, grading, and labor.

Assuming a standard mix design using 1250 kg of aggregate per cubic meter of concrete, the cost saving per cubic meter by replacing 25% of the natural aggregate with RCA is estimated as follows:

Natural aggregate (100%):
1250 kg × \$0.012/kg = \$15.00/m³
RCA at 25% replacement:
937.5 kg (natural) × \$0.012 = \$11.25
312.5 kg (RCA) × \$0.007 = \$2.19
Total = \$13.44/m³
⇒ Savings = \$1.56/m³

When scaled to large construction projects (e.g., 1,000 m³ of concrete), this translates to a cost reduction of approximately \$1,560, excluding further savings from reduced landfill disposal costs, which typically range from \$3 to \$6 per ton of unmanaged debris.

Furthermore, in regions like Iraq, where demolition waste is abundantly available due to war-related destruction, RCA production can be decentralized, allowing contractors to establish on-site crushing units, thus eliminating long-distance hauling costs. Even when accounting for the incremental water and labor cost needed to maintain slump consistency for RCA mixes, the net economic impact remains favorable, particularly at the identified optimal 25% substitution level.

In conclusion, the use of RCA not only contributes to environmental sustainability but also demonstrates tangible economic benefits. The cost reduction per cubic meter, combined with savings in waste disposal and reduced reliance on virgin aggregates, supports the adoption of RCA in both public and private sector construction projects in Iraq and similar developing contexts.

The economic implications of utilizing RCA are particularly relevant in developing regions such as Iraq, where construction and demolition waste is abundant. The study's cost analysis demonstrates a clear financial benefit, with an estimated material cost reduction of \$1.56/m³ at a 25% replacement level, as shown in Table 8. This economic gain is further amplified when scaled to larger volumes and when considering the savings associated with reduced landfill usage and transportation. On-site RCA production through mobile crushing units can significantly lower logistics costs and support decentralized material supply chains. Despite minor increases in water demand and mixing effort to achieve target workability, the overall cost-benefit profile of RCA-concrete remains favorable, especially in post-conflict urban reconstruction contexts where sustainable resource management is paramount.

Table 8. Cost evaluation of RCA replacement

	RCA Replacement (%)	Natural Aggregate (kg)	RCA (kg)	Natural Aggregate Cost (\$)	RCA Cost (\$)	Total Aggregate Cost (\$/m³)	Cost Savings (\$/m³)
1	0	1250.0	0.0	15.0	0.0	15.0	0.0
2	25	937.5	312.5	11.25	2.1875	13.4375	1.5625
3	50	625.0	625.0	7.5	4.375	11.875	3.125
4	75	312.5	937.5	3.75	6.5625	10.3125	4.6875
5	100	0.0	1250.0	0.0	8.75	8.75	6.25

5. CONCLUSIONS

The integration of recycled concrete aggregate (RCA) into structural concrete affects both workability and mechanical performance, necessitating higher water content to maintain standard slump values. Experimental results revealed that a 25% replacement level of both coarse and fine aggregates (C25 and S25) achieves a compaction factor of 96% and maintains 94% and 79% of the reference mix's compressive and tensile strengths, respectively. The concrete mixes were prepared using crushed waste cubes sourced from laboratory rejects, ensuring RCA grading compatibility with conventional aggregates. The testing program encompassed fresh and hardened properties in accordance with ASTM and BS standards. Additionally, an economic analysis demonstrated tangible material cost savings of up to \$1.56/m³ at a 25% RCA replacement rate, with maximum savings of \$6.25/m³ observed at 100% substitution. However, higher RCA content resulted in a significant decline in mechanical performance. Therefore, 25% substitution is identified as the optimum level for achieving a balance between mechanical integrity, workability, and cost efficiency. These findings validate the technical and economic viability of RCA-based concrete, supporting its implementation as a sustainable construction material in regions characterized by high volumes of construction and demolition waste.

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