Experimental Investigation on the Impact of Recycled Concrete Aggregate on Concrete's Compressive Strength

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Highlights

Recycled aggregate RCA from demolished buildings are utilized in this study to create sustainable, eco-friendly concrete that reduces pollution from construction waste.
The study examines how recycled aggregate affects concrete's qualities, particularly its compressive strength.
Analyzed the effect of RCA percentage on the compressive strength in the concrete mixes.

Abstract: Natural concrete aggregate (NCA) and recycled concrete aggregate (RCA) from demolished buildings were used in this study to produce sustainable concrete that reduces construction waste. Replacement ratios of NCA with RCA ranged from 0% to 100%. The study evaluates the effect of RCA on concrete properties, particularly compressive strength, to assess its viability compared with conventional concrete. Results showed that compressive strength decreases as the replacement ratio increases. At 50% RCA, the reduction was only 3.96%, while at 75% and 100% the reductions were 28.6% and 29.06%, respectively. RCA can therefore be used up to 50% without significant compromise in strength or ductility, while higher ratios may require mix design optimization.
Regarding durability, RCA mixes exhibited higher water absorption and porosity compared to NCA mixes, which may affect long-term performance. The use of supplementary cementitious materials and plasticizers can mitigate these effects and enhance durability.
The relative value of recycled concrete aggregate (RCA) depends on several factors, including density, shock resistance, and internal structural characteristics, all of which influence its suitability for industrial specialization and sustainable construction applications. These properties highlight the potential of RCA as an effective

material when properly processed and incorporated into well-designed concrete mixes.

Keywords: Concrete; Recycled Concrete Aggregate; Sustainability; Compressive Strength; Natural Concrete Aggregate; Reconstruction

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التحقيق التجريبي في تأثير الركام الخرساني المعاد تدويره على مقاومة الضغط للخرسانة

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الملخص:

تم استخدام الركام الخرساني الطبيعي (NCA) والركام الخرساني المعاد تدويره (RCA) من المباني المهدمة في هذه الدراسة لإنتاج خرسانة مستدامة تقلل من نفايات البناء. تراوحت نسب الاستبدال بين الركام الطبيعي والمعاد تدويره من 0% إلى 100%. تهدف الدراسة إلى تقييم تأثير الركام المعاد تدويره على خصائص الخرسانة، وخاصة مقاومة الضغط، وذلك لمقارنة جدواه مع الخرسانة التقليدية. أظهرت النتائج أن مقاومة الضغط

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تنخفض مع زيادة نسبة الاستبدال. عند نسبة 50 RCA %كان الانخفاض 3.96% فقط، بينما عند 75% و100% بلغت الانخفاضات 28.6% و29.06% على التوالي. لذلك يمكن استخدام RCA بنسبة تصل إلى 50% دون تأثير كبير على المقاومة أو اللدونة، في حين أن النسب الأعلى قد تتطلب تحسين تصميم الخلطة.

فيما يتعلق بالديمومة، أظهرت الخلطات المحتوية على RCA معدلات امتصاص ماء ونفاذية أعلى مقارنة بالخلطات المحتوية على الركام الطبيعي، مما قد يؤثر على الأداء طويل الأمد. ومع ذلك، فإن استخدام المواد الإسمنتية الإضافية والملدنات يمكن أن يخفف من هذه التأثيرات ويحسن من ديمومة الخرسانة.

تعتمد القيمة النسبية للركام الخرساني المعاد تدويره (RCA) على مجموعة من العوامل مثل الكثافة، ومقاومة الصدمات، وطبيعة البنية الداخلية، وهي عناصر تؤثر في مدى ملاءمته للتخصص الصناعي وتطبيقات البناء المستدام. وتُبرز هذه الخصائص إمكانية اعتماد RCA كمادة فعّالة عند معالجته واستخدامه ضمن خلطات خرسانية مصممة بشكل مناسب.

الكلمات المفتاحية: الخرسانة، الركام الخرساني العاد تدويره، الاستدامة، مقاومة الضغط، الركام الخرساني الطبيعي، إعادة الإعمار.

1. Introduction:

Recent decades have witnessed an increase in environmental awareness and a growing tendency to utilize recycled materials in engineering to achieve sustainability in construction, particularly in the building sector due to its significant consumption of resources and environmental impact. Recycling construction waste resulting from demolitions and armed conflicts has emerged as a crucial approach to reducing waste and promoting sustainability (1,2). Wars have posed major challenges to infrastructure, causing widespread destruction and accumulation of debris, necessitating the pursuit of innovative and sustainable solutions for managing it (3).

In light of the environmental and economic challenges facing the world today, it has become imperative to seek innovative and sustainable solutions in all areas of life. Among these sectors, the construction sector occupies a prominent position due to its high consumption of natural resources and significant environmental impact. In this context, recycling construction waste and rubble resulting from demolition and armed conflicts is one of the leading solutions that contribute to achieving environmental and economic sustainability. Recurring crises and wars in regions such as Kosovo, Serbia, Gaza, Libya, Iraq, and Syria, are among the greatest challenges facing infrastructure and construction projects (4). These conflicts have caused widespread destruction of infrastructure, resulting in the accumulation of massive amounts of rubble. Hence, the need to find effective solutions to manage this rubble and utilize it in innovative and sustainable ways. Demolition debris management is a complex problem that requires integrated solutions that include collection, transportation, treatment, and disposal (5). With the increasing volume of rubble resulting from conflicts and destruction, it has become imperative to find new ways to utilize this material in a way that achieves environmental and economic benefits. Among these solutions, the idea of recycling concrete from demolished buildings and reusing it in construction processes has emerged.

In light of the environmental and economic challenges facing developing countries and the world today, it has become imperative to seek innovative and sustainable solutions in all areas of life. Among these sectors, the construction sector occupies a prominent position due to its high consumption of natural resources and significant environmental impact. In this context, recycling construction waste and rubble resulting from demolition and armed conflicts is one of the leading solutions that contribute to achieving environmental and economic sustainability (6,7).
Recurring crises and wars in regions are among the greatest challenges facing infrastructure and construction projects. These conflicts have caused widespread destruction of infrastructure, resulting in the accumulation of massive amounts of rubble. Finding effective solutions to manage this rubble and utilize it in innovative and sustainable ways.
Demolition debris management is a complex problem that requires integrated solutions that include collection, transportation, treatment, and disposal. With the increasing volume of rubble resulting from conflicts and destruction (8,9), it has become imperative to find new ways to utilize this material in a way that achieves environmental and economic benefits. Among these solutions, the idea of recycling concrete from demolished buildings and reusing it in construction processes has emerged (10,11).
Due to the current environmental and economic challenges, finding sustainable solutions like recycling demolition and construction debris to reduce waste and reuse available resources is important, as it can contribute to reducing environmental impact and achieving sustainability in the construction industry. This experimental test aims to investigate the effect of using RCA on concrete properties and the compressive strength of the specimen (12–16).
The methodology of this research seeks to achieve the following:

1. Evaluating the effectiveness of RCA: Primarily is to evaluate the effectiveness of using recycled aggregate RCA as a substitute for natural aggregate NCA in concrete production. This will be done by comparing the properties of compressive strength of concrete using RCA with those constructed by NCA

2. Analyzing the impact of RCA ratios: By analyzing the effect of different ratios of NCA with RCA (0-50-75-100%) on concrete properties, compression tests conducted on samples to assess the impact of the different ratios on concrete strength.

3. Finding the optimal ratio of RCA: Using the results of experimental and statistical analysis, we will determine the optimal replacement ratio that achieves a balance between environmental and economic benefits and improved concrete properties.

Promoting sustainability by providing innovative solutions that contribute to enhancing sustainability in the construction sector. Throughout using RCA, waste reduction and local resource conservation, thus contributing to environmental and economic sustainability aims.

2. Materials and Methods:

2.1 Review of Literature:

The Higher Institute of Engineering in Lisbon, Portugal, published an article titled "Evaluation of the Durability of Concrete Mixtures Made from Recycled Aggregates (17). The researchers obtained the aggregate by crushing samples of original concrete prepared in the laboratory specifically for this purpose. Capillary and immersion absorption tests were conducted on two concrete mixes. The first was a concrete mix that did not contain recycled aggregate (RCA), and the second was a concrete mix in which the concrete was replaced 100% with recycled aggregate (R100C). They reached the following results: The R100C concrete mix produced a immersion water absorption rate approximately 46% higher. They concluded a correlation between the immersion absorption rate and the replacement rate of natural concrete with recycled aggregate in the concrete mix. The reason for the increase in the percentage of water absorption by immersion in the concrete mixture containing aggregate is due to its structure with greater porosity, which generally leads to an increase in open pores in the concrete mixture. In the water absorption test, the results were presented in graphic curves shown in Fig. 1.

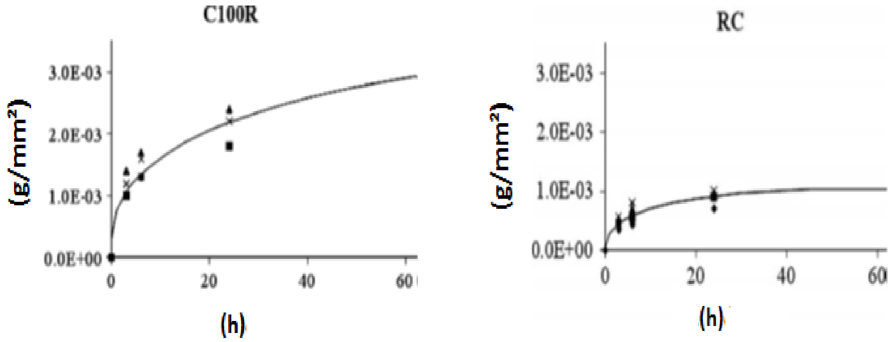

Fig. 1 Water absorption rate

The results showed that R100C mix had an increased absorption rate of 70.3%, this rate was closely related to the amount and percentage of recycled concrete in the mix, which made the mix more porous. R100C mix had a more porous structure and a higher absorption rate, which depended on the amount of aggregates present in the mix. They suggested adding cementations additives instead of ordinary Portland cement, such as silica (carbon dioxide fumes), fly ash, and blast furnace slag, to improve the absorption performance of the resulting mix.

Researchers in The Delhi Technological College, India conducted experiments on the possibility of using RCA extracted from construction and demolition operations to produce concrete (18).

Size classification: All sizes of aggregates, whether good or poor quality, are accepted. They are prepared through primary and secondary crushing to purify and remove impurities, resulting in aggregates with a diameter of 50 mm. These aggregates are then subjected to a second series of crushers to reach diameters ranging from 14 to 20 mm.

Water absorption: The water absorption rate in the recycled mix ranged from 3-12% of the mix. This value was observed to be higher than that of the natural mix, which ranges from 0.5-1%. This is due to the high porosity resulting from sediment adhering to the recycled concrete. Compressive Strength: A decrease in compressive strength, depending on variables such as the type of aggregate used (low or high), the percentage of replacement of natural concrete with recycled concrete in the mix, and the water-to-cement ratio (W/C). In one study, it was found that a high W/C ratio (ranging from 0.75–0.6) in the mix resulted in greater compressive strength and did not differ from the strength of the natural mix, even when the percentage of concrete replacement with aggregate reached approximately 75%. Another study found that the compressive strength of the recycled mix was the same as the natural mix when a W/C ratio higher than 0.55% was used in the mix. However, with a W/C ratio lower than 0.40, the compressive strength value reached up to 75% compared to the value of the natural mix.

Frost and Thaw Resistance: Studies have found that suspended sediments in recycled aggregate do not negatively affect frost and thaw resistance, provided that high-quality recycled aggregates are used.

The Department of Transportation, Washington, D.C., published a special report titled "Using Recycled Aggregates in the Production of Hydraulic Cement Mortar for Use in Pavements." The report examined research on concrete mixes using recycled aggregate and reached the following conclusions (19):

Compressive Strength: The compressive strength of mixes using recycled aggregate was slightly lower than mixes containing natural aggregate, but was generally acceptable. Studies have shown this reduction to be approximately 20% below natural compressive strength, while other studies have shown different results depending on the water-to-cement ratio (W/C) of the mix. Higher air content in the mix also results in lower compressive strength values.

Flexural Strength: The report indicated that the use of recycled coarse aggregate reduces flexural strength by approximately 8% for the same W/C ratio in the mix. The report confirmed that the quality of the aggregate used significantly affects flexural strength and modulus of elasticity.

Modulus of Elasticity: The report found that the modulus of elasticity of mixes containing recycled aggregate was approximately 20-40% lower than that of conventional mixes with the same W/C ratio. This decrease is attributed to the fact that recycled aggregate has a lower modulus of elasticity compared to natural aggregate.

2.2 Research Methodology:

The experimental tests' scope about the impact of RCA on concrete's compressive strength involves many serial stages.

- Selection of RCA and NCA and construction materials. Conducting the lab tests for all materials to verifying it's applied to the required condition and link to sustainability requirements (20).
- Design of concrete specimens containing of RCA and NCA, cylinder samples of (30, 15) cm and Cubes of (10, 10, 10) cm.
- Conduct the compression test on the concrete specimens.
- Analysis of the lab results of specified compression strength.

2.2.1 Selection of RCA and NCA and construction materials:

2.2.1.1 Natural concrete aggregate NCA: is a construction material and a key component used in ordinary concrete mixes. This aggregate is obtained from the crushing of natural rocks, such as granite and basalt Fig. 2. In this research, high quality, graded, crushed, and sharp-edged pebbles with a surface of medium roughness were adopted, taken from the quarries of Hasya area in the rural Homs, conformity to the Syrian Standard Specifications No. (332). year 2007. The maximum size of coarse aggregates 25 mm was used.

Fig. 2 Coarse Aggregate used NCA and RCA

The size range is normally from a few millimeters to several centimeters. Aggregates must be uniform in size and shape and characterized by high strength. NCA must be free of impurities and organic matter that could affect the concrete's properties. The origin of the NCA source is local industry quarries.

2.2.1.2 Recycled concrete aggregate RCA: is produced through recycling demolition and construction debris. This debris is being used as aggregate in concrete mixes.

Use of RCA promotes environmental sustainability by reducing construction waste and reusing local resources. RCA must pass the crushing, cleaning, and screening to have a uniform size and shape and be graded before being used in concrete mixes. Apply the lab test and sieve analysis has been conducted. The maximum size of coarse aggregates 25 mm was used Fig. 3, to ensure the quality of RCA and free impurities and save the concrete performance.

Fig. 3 Lab Test and Sieve Analysis

2.2.1.3 Fine aggregate and Cement: Two type of Local fine aggregate crushed and Natural sand were used. The Ordinary Portland cement (OPC) has been used, corresponding to standard specification-1 No. 3800 in 2015, grade 400 Kg/m3. Free of lumps and moisture. OPC reacts with water to form a strong solid that binds aggregate particles together, contributing to the high strength of concrete.

2.2.1.4 Plasticizer: Type of high-quality chemical plasticizers were used, three proportions (0.5, 1.0, and 1.5) % of cement weight to achieve the required functionality in RCA mixes.

2.2.1.5 Water: must be clean and free of harmful chemicals and impurities. Concrete mixes responded at the ratio W/C = 0.5.

2.2.2 Design of concrete specimens:

Designing concrete mixes throughout using different replacement ratios of NCA and RCA, two steps of preparation:

1. Construction Material Preparation: Prepare and test NCA and RCA, fine aggregate, cement, and water according to the specified mix ratios Fig. 4 . Hand mixing was used thoroughly to ensure a homogeneous mixture. Table 1 shows the proportions of used NCA materials.

Fig. 4 Prepare of NCA and RCA mixes

Table 1 NCA mixes properties

Material	Coarse Aggregate	Fine Aggregate 1	Fine Aggregate 2	Sand
% 0f m3	0.37	0.21	0.27	0.15
Volume of m3	259.37	147.21	189.27	105.15

Specific Weight	2.784	2.811	2.756	2.568
Weight of m3	722.09	413.81	521.63	270.03

Different replacement ratios of RCA were used: 0%, 50%, 75%, and 100%. Table 2 shows the proportions of used RCA materials.

Table 2 RCA mixes properties

Material	Coarse Aggregate	Fine Aggregate 1	Fine Aggregate 2	Sand
% 0f m3	0.28	0.16	0.16	0.21
Volume of m3	196.28	112.16	112.16	147.21
Specific Weight	2.7	2.7	2.7	2.653
Weight of m3	529.96	302.83	302.83	390.55

1. Casting of Concrete Specimens: Casting cylindrical (30, 15) cm and cubic (10, 10, 10) cm samples under laboratory conditions at temperatures up to 25°C Fig. 5. The treated samples are left to cure for 24 hours, and then samples are removed from the molds. Finally, samples are placed in potable water for 28 days.

Fig. 5 Casting Cylindrical and Cubic Samples

2.2.3 Conduct the compression test:

Conducting an axial compression strength test after 28 days of casting Fig. 6. The hydraulic oil machine and the load velocity V=1 kN/s have been used. Recording the maximum capacity of specimens' compression strength and (σ-ε) behavior.

Fig. 6 Compression Strength Test on Concrete Cylindrical

3. Results:

The experimental results of compression strength tests indicate the concrete specimens' capacity, which were designed with different replacement ratios of NCA and RCA (0, 50, 75, and 100%). Descriptive statistics and graphical models were used to illustrate the results. Results in Table 3 below:

The results of laboratory tests of cylindrical and cubic specimens produced of RCA and NCA under axial compression show the contribution of plasticizer on the workability, thus improving the RCA concrete mixes in terms of stress-strain behavior.

By fracture testing of specimens of RCA, the compressive strength of concrete is related to the shape, and the percentage of RCA in the mix composition with the type of plasticizer, where the compressive strength increases with a low percentage of RCA compared to the reference sample without RCA.

The plasticizer in the concrete mixes contributed to an increase in workability and a decrease in W/C ratio, but the percentage increase in strength was due to the type and percentage of RCA. The decrease in compressive strength was observed due to the use of a higher percentage of RCA and W/C as well. This can be explained by the change in the molecular structure of RCA mixtures when the W/C ratio is stable, so it is better to use a lower ratio of RCA and a lower plasticizer percentage and stability by a ratio of W/C.

Table 3 Experimental Results of Lab Tests

% RCA	Specimens Age (days)	Specimens Shape	W/C	% of plasticizer/ Cement	Shape Factor	Compression Strength (MPa)	Average Compression Strength (MPa)	Slump Test cm
%0	28	Cylindrical	0.5	0.5	1	27.30	24.26	11.00
		Cylindrical			1	26.45		
		Cubic(15 cm)			0.8	19.02		
50%	28	Cylindrical	0.5	0.5	1	21.33	23.26	9.50
		Cylindrical			1	27.30		
		Cubic(10 cm)			0.78	21.16		
75%	28	Cylindrical	0.5	1.0	1	17.06	17.32	8.50
		Cubic(10 cm)			0.78	18.81		
		Cubic			0.8	16.07		
100%	28	Cylindrical	0.5	1.5	1	11.52	17.21	7.00
		Cylindrical			1	17.06		
		Cubic(15 cm)			0.8	23.04		

The results clearly demonstrate a progressive decline in compressive strength as the percentage of RCA increases. While the 50% RCA mix showed only a marginal reduction of 3.96% compared to the control mix, the 75% and 100% mixes exhibited significant drops of 28.6% and 29.06%, respectively. This trend aligns with the hypothesis that higher RCA content introduces more porosity and weaker interfacial transition zones (ITZ) due to residual mortar and microcracks in recycled particles.

Moreover, the slump test results indicate a consistent decrease in workability with increasing RCA content. The slump value dropped from 11 cm in the control mix to 7 cm in the 100% RCA mix, reflecting the higher water absorption capacity of RCA. This behavior necessitates the use of plasticizers or water-reducing agents to maintain workability in high-RCA mixes.

The stress-strain behavior also revealed that RCA mixes exhibit a more brittle failure mode, especially at 75% and 100% replacement levels. The peak strain values were lower, and the descending branch of the curve was steeper, indicating reduced ductility. These findings suggest that while RCA can be used up to 50% without major compromise in strength or ductility, higher replacement ratios may require structural compensation or mix design optimization.

Additionally, the variation between cylindrical and cubic specimens was consistent across all mixes, with cylindrical samples showing higher compressive strength. This confirms the influence of specimen geometry on test results and supports the use of standardized cylindrical molds for comparative analysis.

4. Discussion:

The average of the experimental results of compressive strength for samples with 0% of RCA is 24.26 MPa and slump test is 11 cm in fresh status. This value used as a reference for other samples that contain different ratios of RCA.

The average strength of samples with 50% of RCA is 23.27 MPa and slump test is 9.5 cm. A slight decrease in compressive strength by 3.96%, compared to the reference compressive strength. This indicates that using 50% RCA doesn't have a significant negative impact on performance and can be acceptable in some applications.

Decrease in slump test about 13.63% this indicate the additional sloping in workability of sample.

Samples with 75% and 100% of RCA showed an average strength of 17.32 MPa and 17.21 MPa. Noticeable decrease 28.6% and 29.06% respectively compared to the reference sample. A significant fall in compressive strength was observed compared to the reference sample (0%) and to the samples of 50% RCA. This indicates using of 75% and 100% of RCA may have a negative impact on concrete mixes properties.

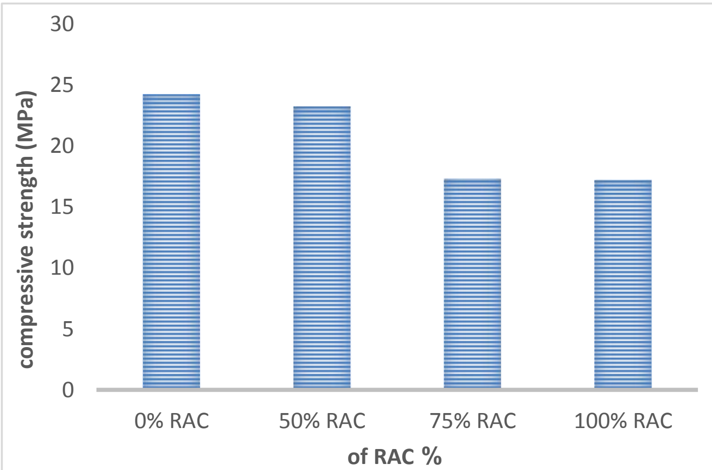

Fig. 7 Descriptive Statistics of Compressive Strength

Results indicate that increasing the RCA percentage caused lower compressive strength of concrete that was clarity in (σ-ε) behavior. That is attributed to the physically changed properties of RCA compared to NCA. So, it is preferable to use an RCA ratio of not more than 50% in the construction applications' high compressive strength requirement.

The shape of the tested specimen had a significant impact on the compressive strength. The cubic specimens have lower strength than the cylindrical specimens. Another perspective: the concrete performance could be affected by the quality of RCA that is related to the treatment methods, as high quality reduces the negative effects on compressive strength.

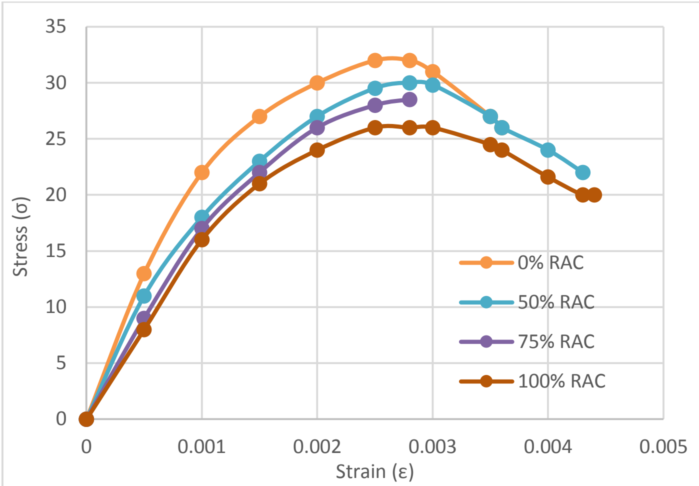

Fig. 8 Stress- Strain (σ-ε) behaviour of Sample

The behavior (σ,ε) of experimental samples is very close to the EURO-CEB standard, and comparing the experimental results of the (σ,ε) with the references curves (21), it was as possible to the EURO-CEB curve. The European Code EN 1992-1-1 presented a mathematical formula. Equation /1/ describing the stress-strain behavior of concrete as a function of the relative strain $\frac{\varepsilon_c}{\varepsilon_{co}}$, and related to the elasticity factor of the material. According to the following:

$$\frac{f_c}{f'_c} = \left[\frac{k\eta-\eta^2}{1+(k-2)\eta}\right] \quad (7)$$

$$\eta = \frac{\varepsilon_c}{\varepsilon_{co}}$$

$$k = 1.05. E_c \frac{\varepsilon_{co}}{f'_c}$$

The behavior of experimental samples with a convergence of up to 95%. It can also verify the conformity of the behaviour experimental samples with the references graphically. Fig. 9 Below are the stress-strain curves of the proposed formula and the experimental sample.

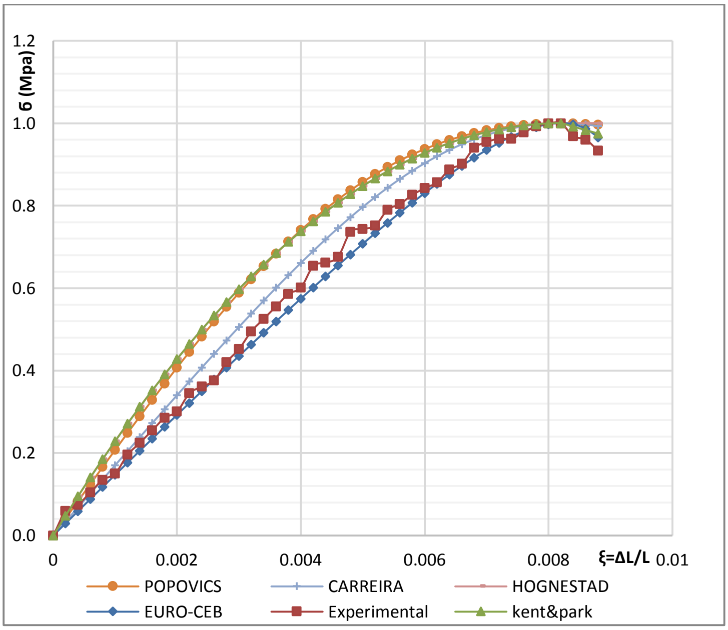

Fig. 9 Stress-Strain Curves of Experimental Samples and References

These findings are consistent with several recent studies. For instance, Khan et al. (2021) reported a similar decline in compressive strength with increasing RCA content, noting a 25–30% reduction at full replacement[22] . Likewise, Ridho et al. (2021) used artificial neural networks to predict compressive strength and confirmed that mixes with over 50% RCA showed significant strength loss due to increased porosity and weaker bonding[23] .

In another study, Shamsoon et al. (2021) observed that RCA mixes exhibited lower modulus of elasticity and flexural strength, aligning with the current study's stress-strain behavior findings[24]. Furthermore, a 2022 study by Zhang et al. demonstrated that the use of supplementary cementitious materials like fly ash can partially mitigate the strength loss in high-RCA mixes, a strategy worth exploring in future work.

These comparisons reinforce the conclusion that RCA can be safely used up to 50% replacement in structural concrete, while higher ratios require careful mix design and performance evaluation.

5. Conclusions and recommendations:

This study analysed the effect of RCA percentage on the compressive strength in the concrete mixes. The recycled aggregate can be used in moderate proportions without significant negative impact on concrete performance. By improving recycling techniques, including the crushing and sorting process of RCA, to ensure particle homogeneity and remove impurities of RCA. Thus, quality control and technical details could be secured to ensure optimal performance. The use of RCA in construction applications can be enhanced to achieve environmental and economic sustainability.
Based on experimental results, it is recommended to use RCA with a percentage not more than 50% in applications with high compressive strength requirements.
The behavior (σ,ε) of experimental samples is very close to the EURO-CEB standard with a convergence of up to 95%.

Acknowledgments: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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Abbreviations:
NCA: Natural Concrete Aggregate
RCA: Recycled Concrete Aggregate
σ-ε: Stress - Strain

Funding:

If there is no fund allocated to the research just use the statement: **No Fund**

Author contributions:

[1*a, 1b] Made the methodology and substantial contribution to the design of the article. The acquisition, analysis, interpretation, and investigation of data. Managed and funded the work. Originally drafted the article, revised it, and edited it critically for important intellectual content.

[1c,1d] Conceived and designed the analysis. Support in the contributed data and analysis tools. Approved the version to be published, Contribution to the design of the article. Support in the contributed data and tools.

Competing interests:

Authors declare that they have no competing interests.

Data and materials availability:

All data are available in the main text or the supplementary materials.