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Comportamiento mecánico del hormigón con áridos reciclados de hormigón
Mechanical behaviour of concrete with recycled concrete aggregates

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Resumen-- **Este trabajo evalúa el comportamiento mecánico del hormigón con áridos reciclados de concreto (RCA), considerando resistencia a compresión, resistencia a flexión y módulo de elasticidad a 28 días. La investigación se desarrolló mediante una revisión sistemática siguiendo la metodología PRISMA, seleccionando cuatro estudios con objetivos y metodologías consistentes. Se tabularon y compararon propiedades mecánicas clave, complementando el análisis con representaciones gráficas para evaluar la influencia de proporciones y tratamientos de RCA. Entre los resultados, la mezcla RCA-0.45-50-4 (MMA) alcanzó 50.58 MPa de resistencia a compresión, 4.90 MPa de resistencia a flexión y 35.98 GPa de módulo de elasticidad con un 50% de RCA. La mezcla CC-R50, tratada con recubrimiento de pasta reciclada y carbonatación acelerada, mostró un desempeño balanceado, con módulo superior al de la mezcla de control y resistencia a compresión próxima. Se concluye que técnicas como la carbonatación acelerada y el uso de fibras de acero mitigan la pérdida de propiedades, consolidando el potencial estructural y sostenible del RCA.**

Palabras clave— Hormigón; agregado reciclado; resistencia a la compresión; resistencia a la flexión; módulo de elasticidad.

Abstract— **This work evaluates the mechanical behaviour of concrete with recycled concrete aggregates (RCA), considering compressive strength, flexural strength, and elasticity modulus at 28 days. The research was developed through a systematic review following the PRISMA methodology, selecting four studies with consistent objectives and methodologies. Key mechanical properties were tabulated and compared, complementing the analysis with graphical representations to assess the influence of RCA proportions and treatments. Among the results, the RCA-0.45-50-4 (MMA) mixture reached 50.58 MPa compressive strength, 4.90 MPa flexural strength and 35.98 GPa modulus of elasticity with 50% RCA. The CC-R50 mixture, treated with recycled paste coating and accelerated carbonation, showed a balanced performance, with modulus superior to that of the control mixture and resistance to close compression. It is concluded that techniques such as accelerated carbonation and the use of steel fibres mitigate the loss of properties, consolidating the structural and sustainable potential of RCA.**

Index Terms— Concrete; recycled aggregate; compression strength; flexural strength; elasticity modulus.

I. INTRODUCTION

THE growing demand for sustainable materials in the construction industry has driven the use of recycled aggregates as a viable alternative to reducing the environmental impact of concrete production. Recent research has extensively explored the mechanical and durability properties of concrete mixtures incorporating recycled aggregates, both fine and coarse, to understand how these mixtures can compete with conventional in structural applications.

Recent studies have analysed the mechanical behaviour of concretes incorporating different proportions of recycled aggregates under innovative techniques. For example, Letelier et al. evaluated the impact of combined coating treatments with recycled pastes and accelerated carbonation on recycled coarse aggregates, (Letelier et al., 2024) highlighting significant improvements in mechanical properties. Benli et al. (Benli et al., 2024) investigated the use of recycled fine aggregates and

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reinforced concrete steel fibres, resulting in improvements in compressive strength, bending strength and durability. Revilla-Cuesta et al. (Revilla-Cuesta et al., 2022) explored the rebound rate as an overall mechanical quality indicator for self-compacting concrete with recycled aggregates, showing its usefulness in comprehensive structural predictions. On the other hand, Jagan et al. (Jagan et al., 2021) compared mixing approaches such as TSMA and MMA to optimize the mechanical performance of concrete with recycled aggregates.

Recycled aggregates present inherent challenges related to their porosity, heterogeneity, and residual mortar adhesion. However, recent studies have shown that these limitations can be mitigated by innovative treatments such as accelerated carbonation, silica nanoparticle pretreatment and optimisation of mixing methods (Pavlů et al., 2023) (Y. Wang & Chen, 2016) (Choi et al., 2021), (Piccinali et al., 2022)These techniques make it possible to improve the mechanical properties and durability of recycled concrete, making it competitive with traditional concretes (Oikonomopoulou et al., 2022), (Sun et al., 2024)

The current literature highlights important developments in this field. For example, Pavlů et al. (Pavlů et al., 2023) evaluated the use of fine recycled aggregates in high-performance concrete, reducing autogenous shrinkage and improving material sustainability. Wang et al(X. Wang et al., 2024) investigated the mechanical properties of recycled low-carbon concrete, demonstrating the relevance of a suitable mixing ratio to optimize compressive strength. Additionally, studies such as Piccinali et al. (Piccinali et al., 2022), Oikonomopoulou et al. (Oikonomopoulou et al., 2022) and Sun et al. (Sun et al., 2024) stress the importance of the selection and treatment of recycled aggregates to ensure their homogeneity and structural compatibility.

The durability of concrete with recycled aggregates has also been the subject of detailed studies. Zhao et al. and Abdo (Abdo et al., 2024) et al. analysed the performance of reinforced concrete beams made from treated recycled aggregates, highlighting a performance comparable to that of natural aggregate beams. Additional research such as Choi et al. (Choi et al., 2021) and Pani et al. (Pani et al., 2020) addresses the environmental and economic implications of using these materials in sustainable construction.

Significant progress has been made in the development of optimised mixtures integrating supplementary materials such as fly ash and silica nanoparticles, which improve the mechanical and durability properties of recycled concrete(Haigh et al., 2024), (Zhang et al., 2022) In addition, Haigh et al. highlighted the use of recycled fibres and modified composites to improve the thermal resistance and sustainability of concrete, underlining the versatility of these technologies.

These studies show the wide potential of recycled aggregates as essential components in sustainable concrete production. In this context, it is particularly relevant to delve into innovative mixing approaches, combined treatments of coarse and fine aggregates, and the use of advanced mechanical quality indicators. This study will focus on comparing the mechanical properties evaluated by Letelier et al.(2024), Benli et al. (2024), Revilla-Cuesta et al. (2022) and Jagan et al. (2021)

In summary, the above-mentioned articles were compiled with the aim of analysing, in this study, the behaviour of the mechanical properties of concrete when incorporating recycled aggregates, based on previous investigations with similar dosages. This analysis is conducted by comparing the tests described in those articles.

II. METHODS

A. *Methodology*

The methodology applied in this research was developed systematically, using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology to conduct an exhaustive search in scientific databases. This approach made it possible to screen and filter the studies into an initial set of 23 relevant articles. Subsequently, a detailed analysis of these studies was conducted to identify similarities in their characteristics, such as the raw material used, the aggregates used, and the tests performed. Based on the above, four scientific articles are selected that share a common approach, where they analyse the mechanical properties of concrete with recycled aggregates, specifically in terms of compressive strength, flexural strength, and elastic modulus.

The criteria for the selection of these four studies are based on the consistency of their objectives and methodologies, as well as the emphasis on the incorporation of recycled aggregates as a main component in concrete mixtures.

This approach is particularly relevant as it allows the mechanical performance of the material to be assessed and represents a significant contribution to sustainability research in construction and materials engineering.

The selection process involved a rigorous comparative analysis of recent scientific publications, with special regard to those studies which apply innovative methods in the treatment of recycled aggregates. Includes work evaluating the impact of these treatments on the mechanical properties of concrete, using standardized tests that provide quantifiable and comparable

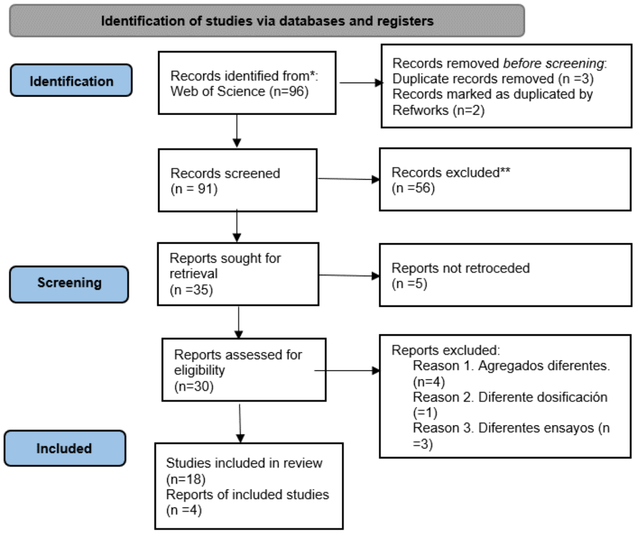

Fig. 1. Flow chart designed. Source: Author’s creation.

results. These tests make it possible to understand the behaviour of the material under different loading conditions and its potential for both structural and non-structural applications.

This analysis highlights the importance of recycled aggregates not only as a sustainable alternative to natural aggregates, but also as a determining factor in modifying the mechanical properties of concrete. The characteristics of aggregates, their preparation and the treatments applied have become a central axis to explore their impact on the strength, flexibility, and rigidity of the material. This has motivated the selection and detailed study of these articles, providing a solid basis for advancing the development of more sustainable and efficient concrete mixtures.

III. MATERIALS AND METHODS

A. Dosages

To synthesize the information based on the dosages of each mixture, table 1 has been prepared. To facilitate a more objective comparison, this table standardizes the dosages as a function of 1 kg/m3 of cement considering proportional values for all its variables according to the data given for each mixture in the selected studies. It also details the types of coarse and fine aggregates used in each, so you can see what they have in common. Furthermore, the presence of superplasticizers in different proportions and other additional aggregates is visualized.

This table makes it possible to observe the characteristics of different concrete mixtures depending on the components used and the proportions applied. One of the highlights is the classification of mixtures according to the percentage of recycled aggregate present, which varies between 0%, 50% and 100%, so that each composition is broken down according to the proportion and type of both fine and coarse aggregates used in each mixture.

Another element to consider is the use of superplasticizer additives, whose proportions vary between mixtures (Letelier et al., 2024),(Benli et al., 2024),(Revilla-Cuesta et al., 2022) Some mixtures also include steel fibres, which appear in specific combinations (Benli et al., 2024). As for additional materials,

TABLE I.
COMPARISON OF STANDARDS USED BY ANALYSED ARTICLE

	Name	**Thick aggregate**					**Thin aggregate**				**Plastic.**	**Steel Fiber**	**Silica Sand**	**Lime filling**	**Lime Powder**	**RCA Powder**
		NA	CA-1	CA-2	NCA	RCA	NA	RCA	RFA	NFA						
1	C00	2.78	-	-	-	0	2.02	-	-	-	0.02	-	-	-	-	-
	CC-R50	1.39	-	-	-	1.39	2	-	-	-	0.02	-	-	-	-	-
	CC-R100	-	-	-	-	2.78	2	-	-	-	0.02	-	-	-	-	-
2	RFAF0	-	1.53	0.81	-	-	-	-	0	2.16	0.001	0	-	-	-	-
	RFA50F0	-	1.49	0.79	-	-	-	-	1.05	1.05	0.001	0	-	-	-	-
	RFA100F0	-	1.46	0.78	-	-	-	-	2.06	0	0.001	0	-	-	-	-
	RFA0F25	-	1.53	0.81	-	-	-	-	0	2.16	0.001	0.06	-	-	-	-
	RFA50F25	-	1.49	0.79	-	-	-	-	1.05	1.05	0.001	0.06	-	-	-	-
	RFA100F25	-	1.46	0.78	-	-	-	-	2.06	0	0.001	0.06	-	-	-	-
	RFA0F50	-	1.53	0.81	-	-	-	-	0	2.16	0.001	0.13	-	-	-	-
	RFA50F50	-	1.49	0.79	-	-	-	-	1.05	1.05	0.001	0.13	-	-	-	-
	RFA100F50	-	1.46	0.78	-	-	-	-	2.06	0	0.001	0.13	-	-	-	-
3	F0	-	-	-	-	1.77	-	0	-	0.02	0.02	-	3.67	0.55	-	-
	F50	-	-	-	-	1.77	-	1.68	-	0.02	0.02	-	1.83	0.55	-	-
	F100	-	-	-	-	1.77	-	3.37	-	0.02	0.02	-	0	0.55	-	-
	L0	-	-	-	-	1.77	-	0	-	0.02	0.02	-	3.13	-	1.12	-
	L50	-	-	-	-	1.77	-	1.45	-	0.02	0.02	-	1.58	-	1.12	-
	L100	-	-	-	-	1.77	-	2.88	-	0.02	0.02	-	0	-	1.12	-
	R0	-	-	-	-	1.77	-	0	-	0.02	0.02	-	3.13	-	-	1.02
	R50	-	-	-	-	1.77	-	1.45	-	0.02	0.02	-	1.58	-	-	1.02
	R100	-	-	-	-	1.77	-	2.88	-	0.02	0.02	-	0	-	-	1.02
4	RCA-0.45-00-2	-	-	-	2.49	0	-	-	1.93	-	-	-	-	-	-	-
	RCA-0.45-50-2	-	-	-	1.25	1.25	-	-	1.93	-	-	-	-	-	-	-
	RCA-0.45-100-2	-	-	-	0	2.49	-	-	1.93	-	-	-	-	-	-	-
	RCA-0.45-00-3	-	-	-	2.49	0	-	-	1.93	-	-	-	-	-	-	-
	RCA-0.45-50-3	-	-	-	1.25	1.25	-	-	1.93	-	-	-	-	-	-	-
	RCA-0.45-100-3	-	-	-	0	2.49	-	-	1.93	-	-	-	-	-	-	-
	RCA-0.45-00-4	-	-	-	2.49	0	-	-	1.93	-	-	-	-	-	-	-
	RCA-0.45-50-4	-	-	-	1.25	1.25	-	-	1.93	-	-	-	-	-	-	-
	RCA-0.45-100-4	-	-	-	0	2.49	-	-	1.93	-	-	-	-	-	-	-
	RCA-0.45-00-5	-	-	-	2.49	0	-	-	1.93	-	-	-	-	-	-	-
	RCA-0.45-50-5	-	-	-	1.25	1.25	-	-	1.93	-	-	-	-	-	-	-
	RCA-0.45-100-5	-	-	-	0	2.49	-	-	1.93	-	-	-	-	-	-	-

*1: , 2: , 3: , 4:

the table details the presence of elements such as silica sand, limestone dust, and RCA dust. Mixtures with a higher percentage of recycled aggregate tend to include RCA dust, while mixtures with natural aggregates make more frequent use of silica sand (Revilla-Cuesta et al., 2022).

B. Cements

The cements used in the studies analysed have characteristics adapted to the specific needs of each research. For example, IP-type Portland-Pozzolanic cement, widely used in the study on accelerated carbonation, is distinguished by incorporating pozzolanic materials that improve its resistance to aggressive chemical agents and prolong the durability of concrete. This type of cement is ideal for environments where chemical resistance is required, such as soils and waters with high concentrations of sulphates, in addition to helping to reduce the environmental impact due to the lower amount of clinker in its composition (Letelier et al., 2024).

On the other hand, Portland cement Type CEM I 42.5 R, used in the analysis of the use of fine recycled aggregates in concrete reinforced with steel fibres, is a pure material without additives that is characterized by its high initial strength. This property makes it suitable for applications where rapid strength development is required, such as precast concrete or structures that require high structural capacity at preliminary stages (Benli et al., 2024).

Likewise, the Ordinary Portland Cement Type CEM I 52.5 R, used in the study on self-compacting concrete, offers even higher strengths, reaching values above 52.5 MPa in 28 days. This cement, with a higher clinker content, is particularly effective in projects requiring high mechanical performance, such as pre-stressed or post-stressed structures, and in cold climates where speed of strength development is crucial (Revilla-Cuesta et al., 2022).

Finally, 43-grade Ordinary Portland cement is a versatile and standard material used in the analysis of the mechanical properties of concrete with recycled aggregates. This cement, with an intermediate strength reaching 43 MPa at 28 days, is suitable for general construction applications such as foundations, columns, and slabs, offering a balance of performance and cost in residential and commercial projects (Jagan et al., 2021)

C. Aggregates

It is considered relevant to describe the aggregates used in the studies, as shown in the mixtures described in Table 1.

The term RCA (Recycled Concrete Aggregate), within the category of coarse aggregates in table 1, refers to recycled aggregates obtained from the crushing of concrete waste from demolished structures such as beams and columns (Letelier et al., 2024),(Revilla-Cuesta et al., 2022),(Jagan et al., 2021) RCA analysed by (Letelier et al. 2024), come from rejected prefabricated panels with a minimum strength of 45 MPa. These aggregates have high porosity and water absorption; characteristics offset by advanced mixing designs that seek to maintain the mechanical properties of concrete. To improve their properties, some lots were subjected to treatments such as coating with recycled paste and accelerated carbonation, reducing their porosity and increasing their density (Letelier et al., 2024).

(Revilla-Cuesta et al. 2023) , analyses RCA obtained from demolished structures, such as beams and columns, with increased water absorption due to the adhering mortar. Washing and saturation treatments are applied to improve their performance in structural concrete, although porosity remains a major challenge (Revilla-Cuesta et al., 2022). (Jagan et al. 2021) in its study, in addition to analysing similar RCA, mixing techniques such as TSMA (Two-Stage Mixing Approach) and MMA (Mortar Mixing Approach) are implemented to reduce porosity and densify the matrix (Jagan et al., 2021)

The aggregate "NFA" (Natural Fine Aggregate) is a natural fine aggregate composed of sand, with low water absorption (0.79%) and high specific gravity (2.70), used as standard reference (Benli et al., 2024), (Jagan et al., 2021)

The aggregate "Coarse NA" (natural coarse aggregate) comes from siliceous rocks and is characterized by its low porosity, with a specific gravity of 2.69 and water absorption of only 1.40%. This aggregate serves as a reference in the evaluation of recycled concrete. "Fine NA" (natural fine aggregate) is a siliceous sand used as standard aggregate in all mixtures. Its specific gravity is 2.54 and has a water absorption of 2.17%, providing good workability and cohesion (Letelier et al., 2024)

The natural coarse aggregates, "CA-1" and "CA-2", come from crushed limestone, with sizes of 5-11 mm and 11-22 mm, respectively. Both have low water absorption and high density, making them ideal for concrete mixtures. On the other hand, "RFA" (Recycled Fine Aggregate) is a recycled fine aggregate obtained from crushed concrete waste. This material has higher porosity, water absorption (2.14%) and lower density (2.58) compared to NFA, which can affect the workability and strength of mixtures (Benli et al., 2024).

The fine RCA, as well as the bulk mentioned above, are recycled aggregates obtained from the crushing of discarded concrete elements. In this case sizes from 0 to 4 mm were used for the thin RCA. They have higher water absorption and residual mortar content compared to natural aggregates, which increases porosity and affects adhesion in the concrete matrix. Although both materials are sustainable and reduce the use of natural resources, their use requires adjustments in concrete mixtures to maintain proper mechanical properties and workability (Revilla-Cuesta et al., 2022).

NCA (Natural Coarse Aggregate) is obtained from crushed rock and is characterized by its low porosity, a specific density of 2.68, and water absorption of only 0.67%. These properties make it an ideal material for good cohesion and high mechanical properties in concrete (Jagan et al., 2021).

D. Experimental testing

This section presents the experimental tests conducted in the four articles analysed, which focus on evaluating the mechanical properties of concrete with recycled aggregates (RCA) and its behaviour under different loading and treatment conditions. The main tests include compressive strength, flexural strength, and modulus of elasticity, all conducted in

TABLE II.
COMPARISON OF STANDARDS USED BY ANALYSED ARTICLE

	Standard	Test	Quantity	Dimensions (cm)
[1]	ASTM C39/C39M-21	Compressive	3	15x30Ø
	ASTM C78/C78M-18	Bending	3	15x15x55
	ASTM C469/C469M-14	Elasticity	3	15x30 Ø
[2]	ASTM C39	Compressive	3	15x30 Ø
	EN 14651	Bending	3	15x15x55
	ASTM C469	Elasticity	3	15x30 Ø
[3]	EN 12390-3	Compressive	2	10x20 Ø
	EN 12390-5	Bending	2	7.5x7.5x27.5
	EN 12390-13	Elasticity	2	10x20 Ø
[4]	ASTM C39	Compressive	3	15x30 Ø
	ASTM C293	Bending	3	10x10x50
	ASTM C469	Elasticity	3	15x30 Ø

accordance with internationally recognized standards.

Compressive strength is assessed using ASTM C39 (Letelier et al., 2024),(Benli et al., 2024),(Jagan et al., 2021) and EN 12390-3 (Revilla-Cuesta et al., 2022), using cylindrical test pieces of 150 mm diameter by 300 mm height or cubic 150 mm side. In these tests, an increasing axial load is applied at a controlled speed, generally between 0.25 MPa/s and 0.6 MPa/s, until failure occurs. Tests are commonly performed at 28 days of curing, providing values expressed in MPa, which reflect the concrete's ability to withstand axial loads.

The flexural strength is measured by load tests at three points as ASTM C78 (Letelier et al., 2024) and EN 12390-5 (Revilla-Cuesta et al., 2022), or at two points as ASTM C293 [4]; using prismatic beams of 150 mm x 150 mm x 500 mm. In the case of fibre-reinforced concrete, standard EN 14651 (Benli et al., 2024) is used, which also evaluates crack propagation behaviour by measuring displacement at the crack mouth (CMOD). The results obtained, expressed in MPa, indicate the concrete's ability to withstand indirect tensile stresses and dynamic loads.

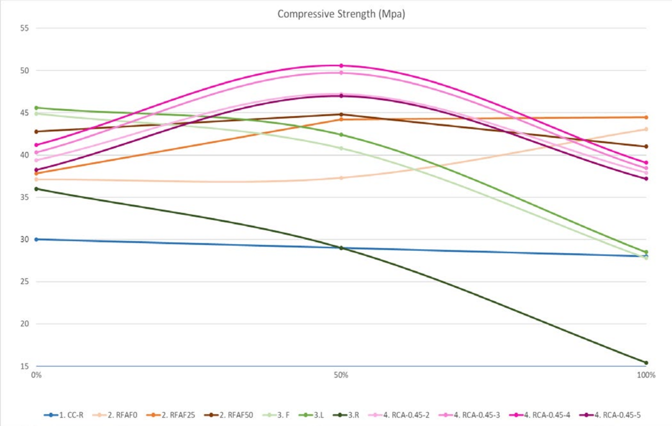

Fig. 2. Compression test graph in selected studies.

The modulus of elasticity is determined by standard ASTM C469 [1-(Benli et al., 2024),(Jagan et al., 2021) or its European equivalent EN 12390-13 (Revilla-Cuesta et al., 2022), using cylindrical test pieces like those used in compression. During the test, a controlled axial load is applied which does not exceed 40% of the compressive strength while axial and lateral deformations are recorded. This method allows to calculate the stiffness of concrete, a crucial parameter for structures where deformation must be minimized.

The test results identified significant differences in the mechanical properties of mixtures with different doses of recycled aggregates and treatments. For example, aggregates subjected to coating and carbonation processes showed better performance in terms of modulus of elasticity and compressive strength compared with untreated aggregates (Letelier et al., 2024)-(Jagan et al., 2021)

In general, these tests demonstrate that although the incorporation of RCA may slightly reduce the mechanical properties compared to conventional concrete, the use of specific treatments and appropriate dosage combinations can mitigate these effects, Making the use of recycled concrete in structural applications feasible. Then, as shown in Table I, a comparative analysis of the types of tests described in the selected articles was conducted with the purpose of selecting those found to be similar, to define the most relevant properties to be compared for each mixture studied.

Similar tests have been highlighted, so it is determined that the comparison of 28-day compression tests, 28-day elasticity modulus and 28-day flexion will be conducted.

IV. RESULTS

A. *Compressive strength*

As can be seen from Fig. 2, the compressive force varies depending on the percentage of recycled aggregate used in the concrete mixture. The trend of the effect of different recycled aggregates on their compressive forces was analysed:

In relation to the shape of the trend lines obtained, it is inferred that they could be quadratic functions, where there is an increase, a peak, and from this a decrease. In this case, the peak would be the optimum value of the aggregate where a higher compressive force is obtained, and from that point on, it decreases. However, there are aggregates which, in the selected proportion, only adversely affect this mechanical property, such as the aggregates 3.F, 3.L and 3. R, as can be seen in the graph.

The compression strength results showed that the CC-R50 series achieved the highest 28-day resistance among RCA blends, followed by the treated CC-R100 series, which was 5.5% more resistant than the untreated R100 series. However,

TABLE III.
COMPRESSIVE STRENGTH RESULTS FOUND IN SELECTED STUDIES

NUM. REF	**[1]**	**[2]**			**[3]**			**[4]**			
Recycled Aggregate (%)	**CC-R**	**RFAF0**	**RFAF25**	**RFAF50**	**F**	**L**	**R**	**RCA-0.45-2**	**RCA-0.45-3**	**RCA-0.45-4**	**RCA-0.45-5**
0%	30	37.11	37.82	42.76	44.9	45.6	36	39.38	40.32	41.21	38.25
50%	29	37.3	44.22	44.82	40.8	42.4	29	47.23	49.73	50.58	47.01
100%	28	43.05	44.47	41	27.8	28.5	15.4	37.9	38.44	39.1	37.19

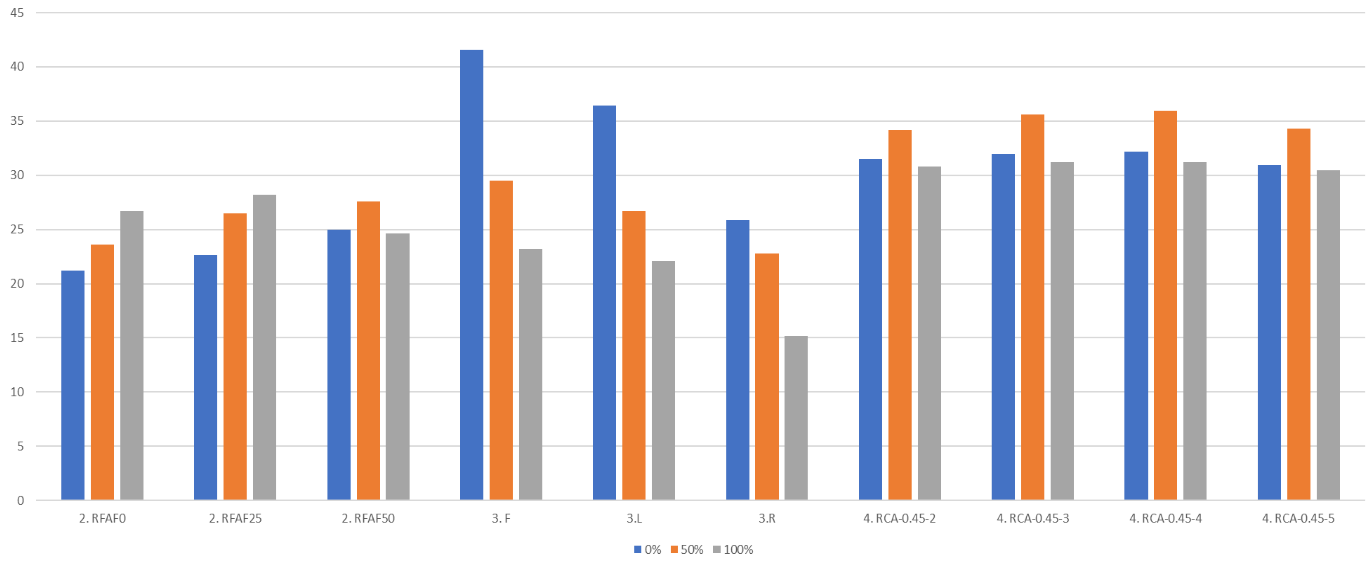

Fig. 3. Young's modulus results in selected studies.

TABLE IV.
YOUNG'S MODULUS DATA FOUND IN SELECTED STUDIES

	[1]		[2]			[3]				[4]	
Recycled aggregate (%)	**R**	**RFAF0**	**RFAF25**	**RFAF50**	**F**	**L**	**R**	**RCA-0.45-2**	**RCA-0.45-3**	**RCA-0.45-4**	**RCA-0.45-5**
0%	-	21.22	22.63	24.97	41.6	36.4	25.9	31.46	31.94	32.15	30.92
50%	-	23.6	26.48	27.58	29.5	26.7	22.8	34.2	35.59	35.98	34.28
100%	-	26.66	28.22	24.66	23.2	22.1	15.2	30.81	31.22	31.25	30.48

all mixtures with RCA had lower resistances than the control series, with differences of 3.7%, 7.6% and 13.5% for CC-R50, CC-R100 and R100, respectively. These results show that coating and carbonation treatments improve the strength of recycled concrete, although their effectiveness is limited by the natural pre-carbonation of RCA (Letelier et al., 2024).

Compression strength improved in most mixtures by replacing natural fine aggregates (NFA) with recycled fine aggregates (RFA) and incorporating steel fibres (SF). The mixture with 50% RFA and 50 kg/m3 SF reached the highest compressive strength (44.82 MPa), 20.7% higher than the reference mixture (RFA0F0). However, the mixture with 100% RFA and 50 kg/m3 SF showed a slight decrease of 4.1%. The internal curing effect of RFA and its ability to fill micro-voids in the concrete matrix improved density and compaction, while steel fibres helped control crack growth and absorb energy during concrete failure. Although 100% replacement of RFA tends to reduce compressive strength due to weaker ITZ and higher water absorption, the combined use of RFA and SF allowed significant improvements in certain combinations, especially with a moderate content of RFA (up to 50%) (Benli et al., 2024).

The use of 100% recycled coarse aggregates (RCA) combined with limestone powder allowed to achieve compressive strengths greater than 40 MPa, which makes it suitable for structural concrete. However, the incorporation of fine RCA negatively affected this property due to increased porosity and lower adhesion between the matrix and aggregates. Mixtures with 50% fine RCA showed a less pronounced decrease in compressive strength compared to those using 100%. The R100 mixture, which included 100% fine RCA and RCA powder, had the lowest compressive strength, reaching only 16 MPa. (Revilla-Cuesta et al., 2022)

The compressive strength reached at 28 days was highest in the RCA-0.45-50-4 (MMA) mixture, which achieved a value of 50.58 MPa. This result demonstrates that the modified mixing technique (MMA) is highly effective in improving the compressive strength of recycled concrete (RCA). The rigid matrix formed during the first step of the mixing process completely covers the surfaces of the RCA, sealing the microcracks in the interfacial transition zone (ITZ). This strengthens the bond between new mortar and recycled aggregates, contributing to excellent mechanical performance under compression (Jagan et al., 2021).

B. *Young's modulus*

The elasticity modulus is a key property for evaluating the mechanical behaviour of concretes with recycled aggregates. Below is the analysis of the articles analysed according to their dosage and the aggregates considered.

The modulus of elasticity of concrete, mainly influenced by porosity and density, showed differences between 2.31% and 5.59% with respect to the 28-day control series. The series with untreated ACR presented the lowest value, while the treated series improved this parameter by 3.5% (CC-R50) and 1.3% (CC-R100) compared to the untreated series. It is noteworthy that CC-R50 slightly exceeded the modulus of elasticity of the control series (C00), while CC-R100 approached this value. These improvements are attributed to the coating and carbonation treatment, which densified the matrix, refined the microporous structure and strengthened the ITZ, reducing water absorption.

These results, consistent with previous studies, indicate that the incorporation of treated RCA can improve the quality of the aggregate and consequently increase the stiffness of the concrete (Letelier et al., 2024).

The drying elastic modulus of concrete mixtures varied between 21.22 GPa and 28.22 GPa. The mixture with 100% RFA and 25 kg/m3 of SF reached the highest elastic modulus, 33% higher than that of the reference mixture (RFA0F0), which presented the lowest value. The use of RFA instead of NFA increased the elastic modulus, with increases of 11.2% and 25.6% for replacements of 50% and 100% of RFA, respectively. In addition, the incorporation of SF significantly improved the elastic modulus, with increases of 32.9% and 16.3% with 100% RFA and 25 kg/m3 and 50 kg/m3 of SF, respectively. These improvements are attributed to the action of interconnection and lateral confinement of steel fibres, which increase the bulk density and reduce the propagation of cracks, strengthening the concrete matrix (Benli et al., 2024)

Mixtures with 100% thick RCA achieved modulus of elasticity above 35 GPa, demonstrating adequate stiffness for structural applications. On the other hand, blends with fine RCA showed significant reductions in this property, especially when combined with high replacement percentages. Mixtures with limestone filler and 100% fine RCA reached a modulus of 15 GPa, while those using limestone powder achieved a slightly higher value of 20 GPa. Overall, mixtures with RCA powder had consistently low performance, with modulus of elasticity around 15 GPa. (Revilla-Cuesta et al., 2022).

The highest modulus of elasticity recorded was 35.98 GPa, again in the RCA-0.45-50-4 (MMA) mix. This value indicates that recycled concrete treated with this mixing technique has a stiffness comparable to concrete with natural aggregates. The reduction of porosity and the coverage of RCA surfaces with a rigid matrix significantly improved the overall stiffness of the concrete. This is crucial for structural applications where stiffness and the ability to resist deformation are key parameters (Jagan et al., 2021).

C. *Flexural strength*

Analysing the bending stress in concrete with recycled aggregates (RAC) is essential to assess its structural viability, especially in elements subjected to bending loads such as slabs and beams. Allows you to compare their performance with conventional concretes, optimize mixing designs, and understand the impact of specific properties of recycled aggregates, such as increased porosity. It also ensures the durability and safety of the material by resisting the spread of cracks, promoting its sustainable use in construction by reducing the consumption of natural resources and waste, and contributing to the development of technical standards that support its adoption.

At 28 days of curing, the control series reached the highest bending strength, while the 50% replacement series (CC-R50) presented the lowest resistance among the tested series. However, the reduction in strength was moderate, with a decrease of 6.6% for CC-R50 and 2.1% for CC-R100 compared to control concrete (C00). The combined treatments managed to improve the mechanical properties of recycled concrete (RAC), reaching values comparable to those of natural concrete, even with high replacement rates. Several studies have confirmed that the flexural strength of RACs is less affected by the quality of recycled aggregates compared to compressive strength, suggesting a higher stability of this parameter in mixtures with RCA (Letelier et al., 2024).

Mixtures with RFA and steel fibres (SF) showed significant improvements in the flexural behaviour of concrete. The mixture with 100% RFA and 50 kg/m3 SF reached the highest maximum load (11.59 MPa, 87.84% higher than the reference) and the highest residual resistances to CMOD of 0.5 mm. On the other hand, the mixture with 50% RFA and 50 kg/m3 SF presented the best residual values in higher CMOD (1.5-3.5 mm). The steel fibres improved bending resistance by limiting crack propagation, increasing load capacity, and reducing load drop after peak. The combination of RFA and SF optimized the

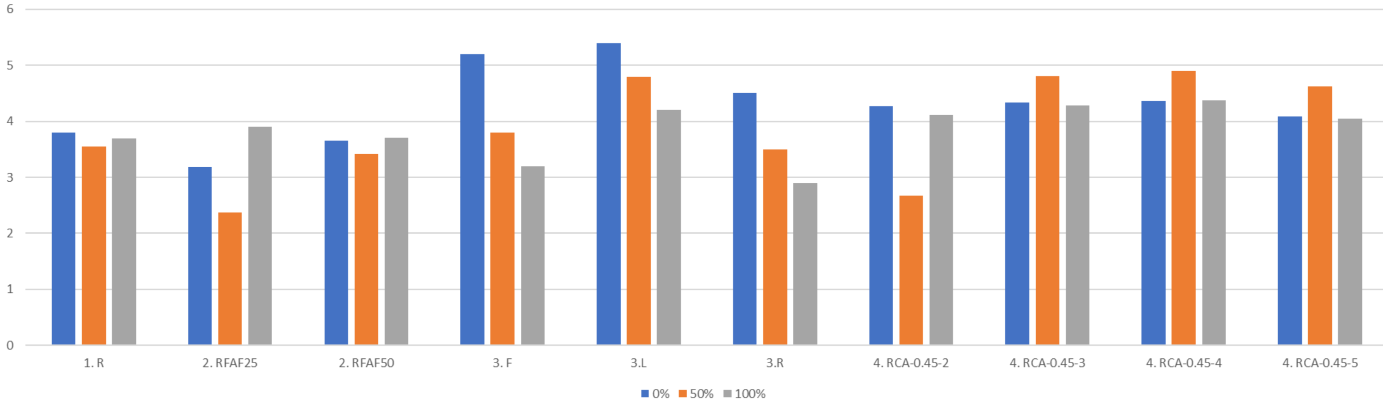

Fig. 4. Graph of bending stress test rods in selected studies

TABLE V.
FLEXURAL STRENGTH TEST DATA FOUND IN SELECTED STUDIES

	[1]		[2]			[3]				[4]	
Recycled aggregate (%)	**R**	**RFAF0**	**RFAF25**	**RFAF50**	**F**	**L**	**R**	**RCA-0.45-2**	**RCA-0.45-3**	**RCA-0.45-4**	**RCA-0.45-5**
0%	3.8		3.19	3.66	5.2	5.4	4.5	4.27	4.33	4.36	4.09
50%	3.55		2.37	3.42	3.8	4.8	3.5	2.68	4.81	4.9	4.62
100%	3.7		3.91	3.71	3.2	4.2	2.9	4.12	4.28	4.37	4.05

energy absorption capacity of concrete, highlighting its potential for demanding structural applications (Benli et al., 2024).

The indirect tensile and bending strengths were in the range of 3 to 5 MPa in mixtures with 100% thick RCA, which is suitable for structural concrete. However, mixtures with fine RCA showed a greater decrease under tensile stresses. In these mixtures, the use of limestone filler combined with fine RCA significantly reduced the flexural strength to 1 MPa, while the limestone powder allowed to reach 2 MPa. Mixtures with RCA powder and high percentages of fine RCA showed similar bending and tensile values, but consistently lower than those without fine RCA. (Revilla-Cuesta et al., 2022).

The flexural strength also showed outstanding values for RCA-0.45-50-4 (MMA) mixture, with a maximum strength of 4.90 MPa. This result highlights the ability of the fibres and treated RCA to manage tensile and bending stresses by improving the quality of the ITZ. The MMA technique favours the formation of a more homogeneous and compact matrix, which distributes stresses better and improves the concrete's ability to resist deformation under bending load. This confirms the suitability of this mixture for applications where bending stresses are critical (Jagan et al., 2021).

V. DISCUSSION

It is considered relevant to compare the mechanical properties of concrete in a graph because with this tool it is possible to analyze and understand the relationships between the variables studied and the performance of the material. By visually representing mechanical properties such as compressive strength, modulus of elasticity or tensile strength, it is possible to identify general patterns and behaviors that are not always evident in data tables. Table 7 shows the data obtained from the trials performed in the studies analyzed.

Table 7 provides the values corresponding to the graphs below. This data allows us to provide a trend line. The trend line, for its part, highlights these relationships indicated above, allowing us to observe whether properties increase or decrease according to the percentage of recycled aggregates. In addition, this tool can be useful for predicting future concrete behaviors under similar conditions, providing a basis for estimating properties in untested scenarios.

A. *Compressive strength vs Young's modulus*

Fig. 5 shows the relationship between compressive strength (MPa) and modulus of elasticity (GPa), which indicates that there is a moderate correlation between these two mechanical properties. In this case, 55.89% of the variability in the modulus of elasticity can be explained by compressive strength.

The positive trend observed in the polynomial line reflects that, as the compressive strength increases, the modulus of elasticity also tends to increase. However, the relatively low value of R2 suggests that there are other significant factors influencing the modulus of elasticity such as aggregate quality,

TABLE VI.
MECHANICAL STRENGTH TEST DATA FOUND IN SELECTED STUDIES

Ref.	Name	Recycled aggregate (%)	Compr. Strength (MPa)	Young's Modulus (GPa)	Flex. Strength (MPa)
[1]	C00	0%	30	-	3.8
	CC-R50	50%	29	-	3.55
	CC-R100	100%	28	-	3.7
[2]	RFAF0	0%	37.11	21.22	-
	RFA50F0	50%	37.3	23.6	-
	RFA100F0	100%	43.05	26.66	-
	RFA0F25	0%	37.82	22.63	3.19
	RFA50F25	50%	44.22	26.48	2.37
	RFA100F25	100%	44.47	28.22	3.91
	RFAF50	0%	42.76	24.97	3.66
	RFA50F50	50%	44.82	27.58	3.42
	RFA100F50	100%	41	24.66	3.71
[3]	F0	0%	44.9	41.6	5.2
	F50	50%	40.8	29.5	3.8
	F100	100%	27.8	23.2	3.2
	L0	0%	45.6	36.4	5.4
	L50	50%	42.4	26.7	4.8
	L100	100%	28.5	22.1	4.2
	R0	0%	36	25.9	4.5
	R50	50%	29	22.8	3.5
	R100	100%	15.4	15.2	2.9
[4]	RCA-0.45-00-2	0%	39.38	31.46	4.27
	RCA-0.45-50-2	50%	47.23	34.2	2.68
	RCA-0.45-100-2	100%	37.9	30.81	4.12
	RCA-0.45-00-3	0%	40.32	31.94	4.33
	RCA-0.45-50-3	50%	49.73	35.59	4.81
	RCA-0.45-100-3	100%	38.44	31.22	4.28
	RCA-0.45-00-4	0%	41.21	32.15	4.36
	RCA-0.45-50-4	50%	50.58	35.98	4.9
	RCA-0.45-100-4	100%	39.1	31.25	4.37
	RCA-0.45-00-5	0%	38.25	30.92	4.09
	RCA-0.45-50-5	50%	47.01	34.28	4.62
	RCA-0.45-100-5	100%	37.19	30.48	4.05

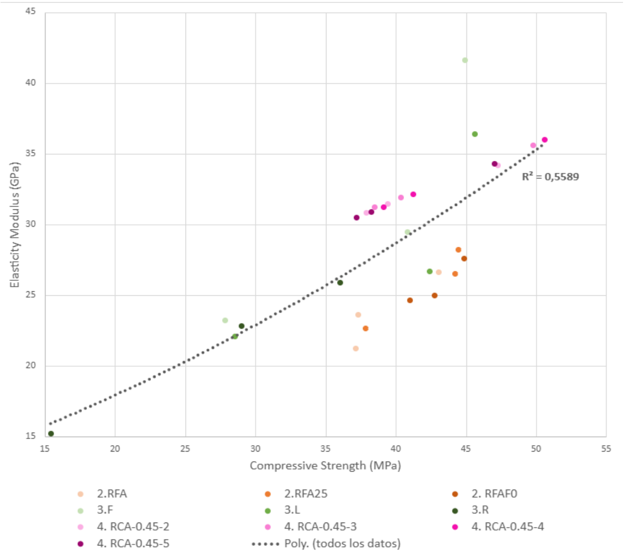

Fig. 5. Comparison and trend line between compression strength test results and modulus of elasticity for the selected studies.

porosity, water/cement ratio, and use of advanced mixing techniques.

In short, although there is a relationship between the compressive strength and the modulus of elasticity, it is not strong enough to reliably predict the modulus of elasticity from compression strength alone. This highlights the importance of considering other parameters in assessing the mechanical behaviour of concrete.

B. *Compressive vs flexural strength*

Fig. 6 shows the relationship between compressive strength (MPa) and flexural strength (MPa), which indicates a weak correlation between these two properties of concrete. Only 16.36% of the variability in flexural strength can be explained by compressive strength in this dataset.

The low correlation suggests that other factors have a significant influence on flexural strength, such as aggregate quality, fiber content, adhesion in the interfacial transition zone (ITZ) and mixing techniques used. Although there is a general trend that an increase in compressive strength tends to slightly improve flexural strength, this relationship is not strong enough to establish reliable predictions between these properties.

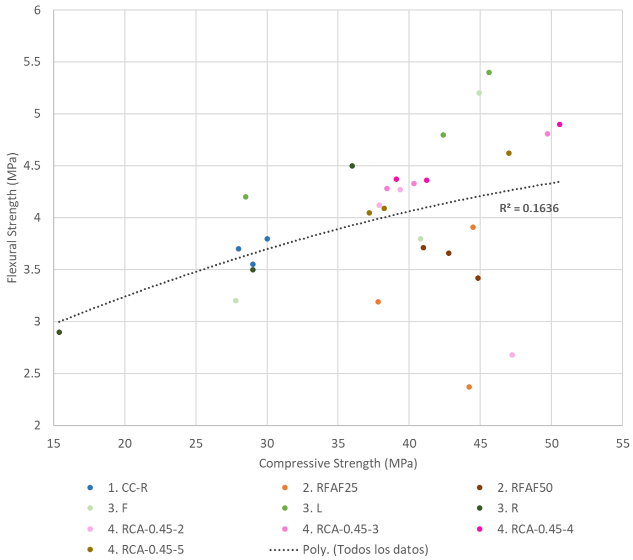

Fig. 6. Comparison and trend line between results of compressive strength and flexural strength tests for selected studies.

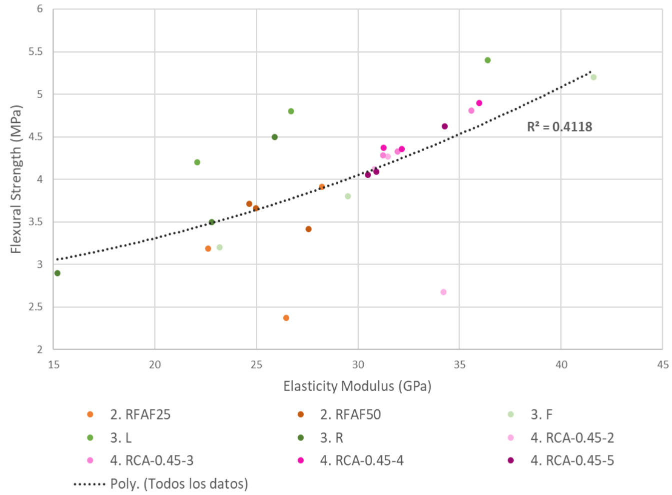

Fig. 7. Comparison and trend line between results of modulus of elasticity and flexural strength tests for selected studies.

The flexural strength seems to be influenced by additional factors beyond compressive strength, which underlines the need to consider these properties independently when assessing the mechanical performance of concrete.

C. *Flexural strength vs Young's modulus*

Fig. 7 shows the relationship between the modulus of elasticity (GPa) and the flexural strength (MPa), which indicates a moderate correlation between these two properties. This means that 41.18% of the variability in flexural strength can be explained by the modulus of elasticity in this data set.

The positive trend observed in the polynomial fit line shows that, as the modulus of elasticity increases, so does the bending resistance. However, the value suggests that there are still additional factors, such as ITZ quality, percentage of recycled aggregates, and mixing techniques, which significantly affect flexural strength and are not fully captured in this relationship.

In conclusion, although there is a moderate relationship between the modulus of elasticity and the flexural strength, this is not strong enough to accurately predict one property based solely on the other. It is necessary to consider other parameters for a comprehensive evaluation of the mechanical performance of concrete.

VI. CONCLUSIONS

The mechanical properties of recycled concrete (RAC) are conditioned by several interrelated factors, among which stand out the quality of the recycled aggregates, the treatments applied, and the mixing techniques employed. Despite initial limitations arising from the increased porosity and weakness of the interfacial transition zone (ITZ) of recycled aggregates, strategies such as accelerated carbonation, coating with recycled paste and use of optimized mixing techniques, as MMA and SEMA, have shown significant ability to improve the mechanical performance of recycled concrete (Letelier et al., 2024),(Jagan et al., 2021)

The compressive strength of mixtures with recycled aggregates reaches its optimum performance with 50% aggregate replacement, as observed in the articles analysed (Jagan et al., 2021) This behaviour is due to the combination of efficient curing, reduction of microcracks in the ITZ and confinement effect provided by applied treatments (Letelier et al., 2024). However, when the replacement percentage of recycled aggregates increases to 100%, the compressive strength decreases significantly, which highlights the importance of establishing an appropriate balance in the proportion and treatment of recycled aggregates (Benli et al., 2024),(Jagan et al., 2021). In terms of modulus of elasticity, treated mixtures show significant improvements compared to unprocessed mixtures. This parameter, which reflects the capacity of concrete to resist deformation, is essential in structural applications [(Letelier et al., 2024),(Revilla-Cuesta et al., 2022),4]. Advanced mixing techniques contribute to the densification of the matrix and increase the stiffness of concrete, reaching values comparable to those observed in conventional concrete (Jagan et al., 2021)

Flexural strength in mixtures with recycled aggregates is less sensitive to the quality of recycled aggregates than compressive strength (Benli et al., 2024; Jagan et al., 2021) This parameter, crucial in elements subjected to tensile forces, can be optimized by incorporating steel fibres, which act as bridges connecting the components of the mixture. This makes it possible to limit the spread of cracks and increase the load capacity after the onset of failure (Benli et al., 2024),(Revilla-Cuesta et al., 2022).

In summary, mechanical properties are largely determined by the interaction of the variables analysed. The moderate correlations observed between compression, flexion and modulus of elasticity underline the need to address these properties independently during the design of recycled concrete mixtures. A comprehensive approach integrating advanced treatments, optimal proportions of recycled aggregates and innovative mixing techniques can mitigate the inherent limitations of recycled aggregates by promoting their efficient use in sustainable structural applications (Letelier et al., 2024)-(Jagan et al., 2021).

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