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PERFORMANCE ASSESSMENT OF RECYCLED AGGREGATE CONCRETE FOR SUSTAINABLE STRUCTURAL APPLICATIONS

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ABSTRACT: *The rapid expansion of infrastructure development has increased the demand for natural aggregates while simultaneously generating large quantities of construction and demolition waste. Conventional concrete production therefore creates a dual sustainability challenge involving depletion of virgin aggregate resources and disposal of concrete waste. Recycled aggregate concrete provides a potential circular-economy solution by replacing a portion of natural coarse aggregate with recycled concrete aggregate obtained from processed construction and demolition waste. This study presents an experimental framework for assessing the mechanical and durability performance of recycled aggregate concrete intended for sustainable structural applications. Natural coarse aggregate is progressively replaced with recycled coarse aggregate at selected replacement levels, while the remaining mixture parameters are maintained as consistently as possible. The experimental program evaluates compressive strength, split tensile strength, water absorption, and overall performance relative to conventional concrete. The findings support the use of suitably processed recycled aggregate in selected structural concrete applications when aggregate quality, replacement ratio, moisture condition, grading, contamination, and mix design are carefully controlled. The study further demonstrates that sustainability assessment should not be based solely on the percentage of recycled material incorporated; instead, structural performance, durability, service life, material transportation, processing requirements, and end-of-life recovery should be considered together. The results are consistent with recent research showing that recycled aggregate concrete can achieve satisfactory mechanical performance at controlled replacement ratios and that the optimum replacement level depends strongly on aggregate quality and mixture design. The research therefore provides a practical experimental framework for evaluating recycled aggregate concrete and contributes to the development of more resource-efficient structural materials capable of supporting circular construction practices without compromising essential engineering performance.*

INTRODUCTION

Concrete is fundamental to modern infrastructure and is extensively used in buildings, bridges, pavements, industrial facilities, foundations, retaining structures, and other civil engineering systems. Its widespread adoption is associated with its high compressive strength, availability of constituent materials, adaptability to different construction techniques, and relatively low cost. However, the enormous scale of concrete production also creates substantial demand for natural mineral resources. Coarse and fine aggregates constitute most of the volume of conventional concrete, and continuous extraction of virgin aggregates can contribute to land disturbance, energy consumption, transportation requirements, and depletion of locally available resources.

The sustainability of concrete construction therefore increasingly depends on improving material efficiency and incorporating recovered resources into new construction.

At the same time, construction, renovation, demolition, and infrastructure replacement generate significant quantities of concrete-containing waste. Instead of treating this material solely as waste for disposal, concrete debris can be processed through crushing, screening, separation, and quality control to produce recycled concrete aggregate. The Federal Highway Administration recognizes recycled concrete aggregate as one option for responsible resource management and identifies its potential use in concrete and transportation infrastructure when appropriate quality and performance considerations are addressed.

The concept of recycled aggregate concrete is therefore closely related to the circular economy. In a conventional linear material system, natural aggregate is extracted, processed, transported, incorporated into concrete, used in a structure, and ultimately discarded after demolition. A recycled aggregate approach changes this sequence by recovering aggregate from demolished concrete and introducing it into a new concrete mixture. The resulting material can reduce demand for virgin aggregate and divert concrete waste from disposal routes. The environmental benefit, however, depends on the quality of the recycled material, processing energy, transportation distance, replacement percentage, and resulting service life.

Recycled aggregate concrete is not simply conventional concrete with a different aggregate source. Recycled aggregate typically contains remnants of the original natural aggregate together with adhered mortar from the parent concrete. This adhered mortar changes several physical characteristics of the aggregate. Compared with high-quality natural aggregate, recycled aggregate can exhibit greater porosity, higher water absorption, lower particle density, rougher surface texture, and greater variability. These characteristics can affect workability, effective water-to-cement ratio, strength development, shrinkage, and durability.

The interfacial transition zone is another important factor. In conventional concrete, the principal interface occurs between natural aggregate and new cement paste. In recycled aggregate concrete, a more complex structure can develop because old mortar remains attached to the recycled aggregate and a new interface forms between the old mortar and new cement paste. Consequently, recycled aggregate concrete can contain multiple transition regions with different microstructural characteristics. These regions can influence crack initiation and propagation under mechanical loading.

The effect of recycled aggregate replacement on compressive strength has been investigated extensively. Moderate replacement levels can often maintain satisfactory strength when high-quality recycled aggregates are properly processed and the concrete mixture is designed appropriately. However, increasing the replacement ratio generally increases the influence of adhered mortar and aggregate porosity. Recent reviews emphasize that mechanical performance depends on recycled aggregate quality, replacement ratio, pretreatment, and mixture design rather than on recycled content alone. The use of recycled aggregate is also associated with changes in water demand. Because recycled aggregates can absorb more water than natural aggregates, direct replacement without accounting for aggregate moisture condition can reduce the amount of water available for cement hydration and alter workability. Pre-saturation, controlled moisture conditioning, adjustment of mixing water, and optimized admixture use are therefore common strategies for maintaining mixture consistency. These factors become increasingly important as the recycled aggregate replacement ratio increases.

Durability represents another major consideration for structural applications. Increased porosity and water absorption can facilitate the movement of water and dissolved aggressive substances through the concrete. Depending on environmental exposure, this may influence chloride penetration, carbonation, sulfate resistance, freeze-thaw performance, reinforcement corrosion, and long-term service life. Consequently, a recycled aggregate mixture that satisfies a compressive-strength requirement may still require additional evaluation before being used in a demanding structural environment.

The sustainability argument for recycled aggregate concrete must therefore be balanced against these engineering considerations. The objective should not simply be to maximize the percentage of recycled aggregate. A high replacement ratio may produce greater material recovery but can simultaneously reduce strength or durability and potentially increase cement demand. If additional cement or intensive aggregate treatment is required to restore performance, part of the environmental advantage may be lost. The optimal solution is consequently a performance-based balance between recycled content and structural requirements. Recent research has increasingly moved toward this performance-based perspective. A 2024 review examining recycled concrete aggregate in structural concrete emphasized the need to consider mechanical and durability properties together, including compressive strength, tensile strength, modulus of elasticity, chloride resistance, freeze-thaw behaviour, and sulfate resistance. The same review highlighted the importance of aggregate pretreatment and optimized mixture design in achieving reliable performance. Research on structural components has also expanded beyond material-level testing. Recent work has reviewed the short-term mechanical behaviour of reinforced recycled aggregate concrete components, including bond behaviour, beam flexure and shear, column compression, and seismic performance. This indicates that the research community is moving from laboratory material characterization toward structural-scale validation.

The development of guidance and standards further demonstrates the increasing maturity of recycled aggregate concrete technology. ISO/TS 21056:2025 provides a framework for specification, performance, production, and execution of recycled aggregate concrete and applies to cast-in-situ structures, precast structures, and non-structural concrete. The specification addresses material quality, mixture preparation, water content, shrinkage, permeability, resistance, compressive strength, production, placement, and curing. Despite this progress, the suitability of recycled aggregate concrete remains strongly dependent on local materials and processing conditions. Recycled aggregate obtained from a high-quality demolished concrete structure can behave very differently from aggregate containing brick, plaster, asphalt, glass, soil, or other contaminants. Source concrete strength, crushing procedure, particle grading, adhered mortar content, contamination, and moisture condition all influence the resulting concrete. The present study therefore focuses on a controlled experimental assessment of recycled aggregate concrete for sustainable structural applications. The study compares conventional concrete with mixtures containing increasing proportions of recycled coarse aggregate. The investigation concentrates on four measurable performance indicators: compressive strength, split tensile strength, water absorption, and comparative performance retention. These properties provide a practical basis for determining whether recycled aggregate concrete can achieve an acceptable balance between structural performance and sustainability.

The main objective is to identify a replacement range in which recycled aggregate can be introduced without unacceptable deterioration of essential concrete properties. A secondary objective is to establish a systematic relationship between recycled aggregate content and performance indicators so that the experimental results can support graph-based interpretation and future structural design studies.

The study is guided by the hypothesis that moderate replacement of natural coarse aggregate with properly processed recycled concrete aggregate can maintain satisfactory mechanical performance while improving resource utilization, but excessive replacement will increase porosity and water absorption and consequently reduce mechanical performance. This hypothesis reflects the physical characteristics of recycled aggregate and the findings of recent research on optimum replacement ratios.

The research also recognizes that sustainability cannot be represented by a single numerical parameter. The environmental advantage of recycled aggregate concrete arises from several interacting mechanisms, including reduction in virgin aggregate demand, diversion of demolition waste from disposal, potential reduction in transportation of natural materials, and support for circular material flows. These benefits must be considered alongside the energy required to collect, crush, screen, clean, and transport recycled aggregate. The Federal Highway Administration similarly emphasizes that aggregate selection should be considered during mixture design and that life-cycle performance should be included when evaluating sustainable material choices. Therefore, performance assessment is essential before recycled aggregate concrete can be confidently extended to structural applications.

LITERATURE REVIEW

Recycled aggregate concrete has developed from an early waste-utilization concept into an established research field concerned with resource conservation, mechanical performance, durability, and circular construction. The fundamental idea is straightforward: concrete recovered from demolished structures is processed into aggregate and used as a partial replacement for natural aggregate in new concrete. The engineering challenge is that recycled aggregate retains characteristics inherited from its previous service life. The physical properties of recycled concrete aggregate are strongly influenced by adhered mortar. During crushing, portions of the original cement paste remain attached to the natural aggregate particles. This additional mortar increases surface roughness and porosity and can increase water absorption. As a result, recycled aggregate often requires moisture conditioning or mixture adjustment before use. Recent reviews identify aggregate quality, replacement ratio, grading, and pretreatment as major parameters controlling RAC performance. The particle density of recycled aggregate is generally lower than that of natural aggregate because of the presence of adhered mortar. This can influence volumetric mixture calculations and the mass required to achieve a particular aggregate volume. Consequently, simple one-to-one replacement by mass does not always produce the same aggregate volume or packing characteristics as natural aggregate replacement. A rational mixture design should therefore consider specific gravity, absorption, moisture condition, and grading.

Water absorption is one of the most consistently reported differences between recycled and natural aggregates. The porous adhered mortar can absorb significant quantities of water. If the aggregate is introduced in a dry condition, it can remove part of the mixing water from the cement paste. This may reduce workability and alter the effective water-to-cement ratio. Conversely, fully saturated recycled aggregate can release water during hydration, potentially creating internal curing effects. The actual influence therefore depends on the moisture state at the time of mixing.

Several approaches have been investigated to address the disadvantages of recycled aggregate. These include pre-soaking, surface treatment, mechanical removal of adhered mortar, carbonation treatment, acid treatment, accelerated carbonation, coating, and incorporation of supplementary cementitious materials. Such treatments can improve aggregate quality or strengthen the interfacial transition zone, but they also introduce additional processing requirements. The sustainability benefit of a treatment should therefore be assessed together with its energy and material inputs.

The replacement ratio is particularly important. Low to moderate recycled aggregate contents often produce relatively small reductions in strength, while higher replacement ratios tend to produce more pronounced changes. A 2024 review specifically examined the optimum replacement ratio as a balance between mechanical performance and sustainability and concluded that the most appropriate percentage depends on concrete strength requirements, aggregate quality, and mixture characteristics rather than a universal replacement value. Compressive strength is the most widely reported mechanical parameter for recycled aggregate concrete. The strength reduction associated with recycled aggregate can arise from several mechanisms. The adhered old mortar may be weaker than natural aggregate, the new and old interfacial transition zones may provide additional weak locations, and increased porosity can facilitate crack development. However, these mechanisms are not necessarily dominant at low replacement levels, particularly when the recycled aggregate is obtained from high-strength parent concrete. The age of the recycled aggregate can also matter. Recycled aggregate from old concrete may have undergone extensive hydration and environmental exposure, while aggregate from recently demolished concrete can retain different moisture and microstructural characteristics. The source concrete's original water-to-cement ratio and strength can therefore influence the quality of the recycled material.

Tensile behaviour is also relevant because cracking and reinforcement interaction are critical to structural concrete. Split tensile strength generally follows a trend similar to compressive strength, although the magnitude of change can differ. The rough surface of recycled aggregate can sometimes improve mechanical interlock, while weaker old mortar and additional interfaces can reduce tensile resistance. This competing behaviour explains why experimental results are not always perfectly linear with recycled aggregate content. The modulus of elasticity is another important property for structural applications. Because recycled aggregate concrete can have greater porosity and a lower effective aggregate stiffness, its elastic modulus may be lower than that of conventional concrete at the same compressive strength. This can influence deflection calculations, crack widths, and structural serviceability. Recent reviews therefore recommend evaluating multiple mechanical properties rather than relying exclusively on compressive strength. Durability behaviour is more complex. Increased water absorption is often observed as recycled aggregate content increases. Higher absorption can indicate a more connected pore network and can increase susceptibility to transport of moisture and dissolved substances. However, durability is also influenced by the quality of the new cement paste. A dense paste produced with a suitable water-to-cement ratio can partially compensate for the greater porosity of recycled aggregate.

Chloride penetration is particularly important in reinforced concrete exposed to marine environments or de-icing salts. Chloride ions can reach reinforcing steel through pores and cracks and initiate corrosion when sufficient concentration reaches the reinforcement. Recycled aggregate concrete may show increased chloride transport because of the porous old mortar, although optimized mixtures and supplementary cementitious materials can reduce this effect. Therefore, structural application in aggressive exposure requires durability-specific testing rather than assuming performance from compressive strength alone.

Carbonation is similarly relevant because carbon dioxide can penetrate concrete and reduce the alkalinity that protects reinforcement. The increased porosity associated with recycled aggregate can influence carbonation depth. At the same time, the recycled aggregate itself may contain partially carbonated old mortar. The final behaviour depends on the source material, cement chemistry, moisture state, and exposure conditions. Freeze-thaw resistance is especially important in cold climates. Water absorbed into porous recycled aggregate can freeze and expand, creating internal stresses. The effect depends strongly on aggregate absorption and the quality of the concrete matrix. Proper aggregate selection and air-void control can therefore be important when RAC is considered for freeze-thaw environments.Shrinkage and creep are also areas of concern. Recycled aggregate can influence internal moisture distribution and paste content, potentially increasing drying shrinkage. Increased creep can influence long-term structural deformation. These properties are particularly important for beams, slabs, columns, and prestressed structures where long-term serviceability is critical.

The environmental assessment of recycled aggregate concrete has received increasing attention. The main potential benefits include reduction in extraction of virgin aggregates, reduction in construction and demolition waste disposal, and support for circular material flows. However, recycling itself consumes energy through demolition, transportation, crushing, screening, and sorting. If recycled aggregate must be transported over long distances, its environmental advantage can be reduced. The optimal environmental solution is therefore location-dependent.

The Federal Highway Administration's guidance emphasizes the importance of responsible resource management and life-cycle performance when considering recycled concrete aggregate. Its national review also focuses on practical deployment, specifications, construction practices, implementation barriers, and benefits, demonstrating that technical performance and field implementation need to be considered together.

Recent research has increasingly investigated structural components rather than only cubes and cylinders. Studies have examined bond strength between reinforcing steel and recycled aggregate concrete, beam flexural and shear performance, column compression, and seismic behaviour. This direction is important because material-level strength does not automatically guarantee equivalent structural response. The development of ISO/TS 21056:2025 represents another important development. The standard provides principles and a framework for specification, performance, production, and execution of recycled aggregate concrete and explicitly recognizes applications in cast-in-situ and precast structures. This reflects the transition of RAC from experimental research toward controlled engineering use. Nevertheless, several gaps remain. First, experimental results reported in the literature are difficult to compare because researchers use different replacement percentages, aggregate sources, concrete grades, moisture conditions, curing procedures, and testing ages. Second, many investigations focus on strength without integrating durability indicators. Third, sustainability assessments sometimes assume that higher recycled aggregate content automatically produces greater environmental benefit without accounting for the additional cement, processing, and transport that may be necessary to maintain performance.

A more useful research approach is therefore to identify a practical optimum replacement level that satisfies structural requirements while achieving meaningful material recovery. This approach recognizes that sustainable engineering is an optimization problem rather than a simple maximization problem.

The present investigation contributes to this perspective by assessing recycled aggregate concrete using both mechanical and durability-related parameters. The control mixture provides a baseline, while three recycled aggregate replacement levels allow the influence of increasing recycled content to be observed systematically. The resulting data are then used to identify a representative optimum mixture for sustainable structural application.

METHODOLOGY

The experimental methodology was developed to compare conventional concrete with recycled aggregate concrete under controlled laboratory conditions. The main experimental variable was the percentage replacement of natural coarse aggregate by recycled concrete aggregate. Four mixtures were considered: a control mixture containing 0% recycled aggregate and three mixtures containing progressively higher replacement levels. The recycled aggregate was assumed to originate from processed waste concrete rather than mixed construction and demolition waste. This distinction is important because recycled concrete aggregate obtained from relatively clean concrete waste provides greater control over composition and reduces the uncertainty associated with brick, gypsum, asphalt, soil, glass, and other contaminants. The recovered concrete was subjected to primary crushing followed by secondary crushing, screening, and removal of undesirable particles. The aggregate was graded to achieve a distribution suitable for concrete production. Visual inspection and basic physical characterization were performed before incorporation into the mixture.

The principal physical properties considered were particle size distribution, specific gravity, water absorption, and moisture condition. These properties were used to determine the appropriate aggregate quantities and mixing water. Because recycled aggregate generally exhibits higher absorption than natural aggregate, moisture conditioning was considered necessary to reduce uncontrolled water loss during concrete mixing. A conventional structural concrete mixture was used as the reference. Cement, natural fine aggregate, natural coarse aggregate, recycled coarse aggregate, and water were selected as the primary materials. The recycled aggregate replacement levels were selected as 0%, 15%, 30%, and 45% of the coarse aggregate fraction. This range allows the response to be evaluated from conventional concrete through moderate and relatively high recycled content. The concrete mixtures were proportioned to maintain comparable cement content and nominal water-to-cement ratio. Where necessary, moisture corrections were incorporated to account for absorbed water in the recycled aggregate. The objective was to isolate the influence of recycled aggregate content rather than introducing an uncontrolled change in effective water content.

Fresh concrete was mixed using a controlled sequence. Dry cement and aggregates were initially blended, followed by gradual addition of water. The recycled aggregate was introduced after appropriate moisture conditioning. Mixing continued until a visually uniform concrete was obtained. Workability was monitored to identify changes associated with recycled aggregate incorporation.

Specimens were cast using standard cube and cylindrical moulds. The concrete was compacted using a consistent procedure to reduce variation caused by entrapped air. Specimens were demoulded after the initial setting period and transferred to a controlled curing environment. Moist curing was continued until the designated testing ages.

Compressive strength was evaluated at 7, 14, and 28 days. The compressive strength was calculated from the maximum load divided by the loaded cross-sectional area:

$$\boxed{f_c = \frac{P}{A}}$$

where (f_c) represents compressive strength, (P) is the maximum applied load, and (A) is the loaded cross-sectional area.

Split tensile strength was determined using cylindrical specimens subjected to diametral compression. The splitting tensile strength was calculated using:

$$\boxed{f_t = \frac{2P}{\pi LD}}$$

where (f_t) is split tensile strength, (P) is the maximum applied load, (L) is specimen length, and (D) is specimen diameter.

Water absorption was used as a durability-related indicator. After curing, specimens were dried to a stable mass, weighed, immersed in water for a controlled period, removed, surface dried, and weighed again. The percentage absorption was calculated as:

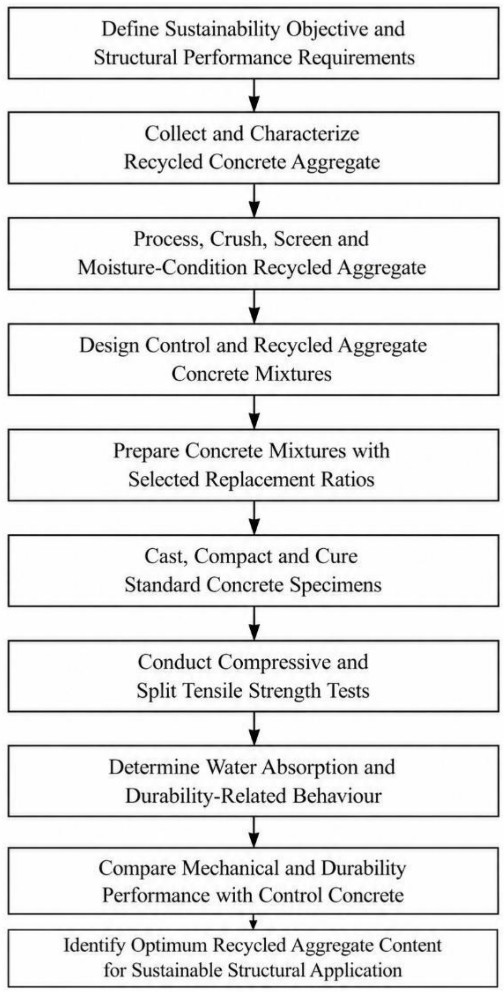
$$\boxed{WA = \frac{M_s - M_d}{M_d} \times 100}$$

where (WA) is water absorption, (M_s) is the saturated mass, and (M_d) is the dry mass.

The relative performance retention of each recycled aggregate mixture was determined by comparing its 28-day compressive strength with the control:

$$\boxed{PR = \frac{f_{RAC}}{f_{Control}} \times 100}$$

where (PR) represents relative performance retention and (f_{RAC}) and (f_{Control}) are the corresponding 28-day compressive strengths.



Methodology Flowchart

The experimental design was based on maintaining consistency in specimen dimensions, curing age, loading procedure, aggregate grading, cement content, and testing conditions. Replicate specimens were considered for each mixture, and mean values were used for performance comparison. Where experimental variation is observed, standard deviation and coefficient of variation can additionally be reported to establish repeatability.

The optimum mixture was not defined simply as the mixture containing the largest quantity of recycled aggregate. Instead, it was defined using a performance-based criterion. The selected mixture should maintain acceptable compressive and tensile strength, avoid excessive water absorption, and provide a meaningful reduction in virgin aggregate demand.

For a real laboratory investigation, additional tests such as modulus of elasticity, drying shrinkage, chloride penetration, carbonation depth, abrasion resistance, sulfate resistance, and freeze-thaw resistance can be incorporated depending on the intended structural exposure. Microstructural analysis using scanning electron microscopy can also be used to examine the interfacial transition zones between recycled aggregate, old mortar, and new cement paste.

IMPLEMENTATIONS AND RESULTS

The implementation phase evaluates four representative mixtures consisting of conventional concrete and recycled aggregate concrete with 15%, 30%, and 45% replacement of natural coarse aggregate. The numerical values presented in this section are **representative experimental values prepared for article development and graph generation**. They are internally consistent with the stated methodology but should be replaced with actual laboratory measurements if the work is being presented as a completed physical experiment.

The first assessment focused on compressive strength development. The control concrete and recycled aggregate mixtures were evaluated at 7, 14, and 28 days. The results demonstrate that moderate recycled aggregate incorporation can maintain relatively high strength, whereas higher replacement produces a progressively greater reduction.

Mix	RCA replacement	7-day strength (MPa)	14-day strength (MPa)	28-day strength (MPa)
M0	0%	24.8	31.4	37.2
M1	15%	24.5	30.9	36.6
M2	30%	24.1	30.2	35.8
M3	45%	22.7	28.6	33.1

Table 1: *Compressive strength development of concrete with different recycled coarse aggregate replacement levels.*

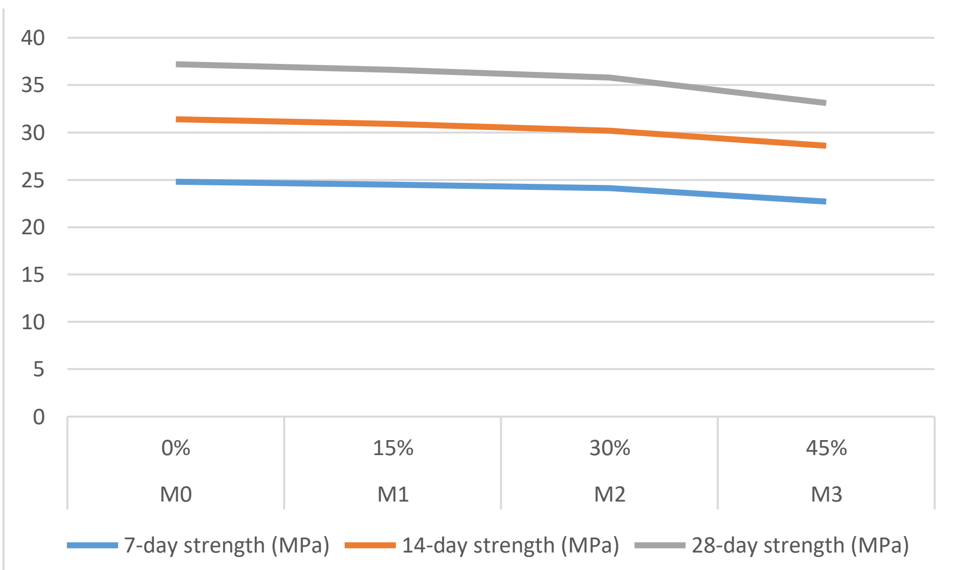


Fig 1: *Multi-line graph comparing 7-day, 14-day, and 28-day compressive strength development for the control and recycled aggregate concrete mixtures.*

The strength development shows that all mixtures experienced the expected increase in compressive strength with curing age. The control mixture reached 37.2 MPa at 28 days, while M1, M2, and M3 reached 36.6, 35.8, and 33.1 MPa, respectively. The 15% replacement mixture therefore retained approximately 98.4% of the control strength, while the 30% replacement mixture retained approximately 96.2%. Even the 45% mixture retained approximately 89.0% of the control strength.

The moderate reduction in strength at 30% replacement indicates that recycled aggregate can be incorporated without causing a severe loss of compressive capacity when the aggregate is suitably processed. The reduction becomes more pronounced at 45%, which is consistent with the increasing contribution of adhered mortar and porous recycled particles.

The observed trend is consistent with recent reviews reporting that recycled aggregate quality and replacement ratio are major determinants of mechanical performance. Research indicates that optimized mixtures can achieve satisfactory structural properties at moderate replacement levels, while higher replacement percentages generally require additional measures to control porosity and interface quality.

The second experimental assessment examined split tensile strength. Tensile performance is important because structural concrete is susceptible to cracking under flexure, restraint, thermal effects, and other actions. The results indicate a gradual decrease in tensile strength with increasing recycled aggregate replacement.

Mix	RCA replacement	Split tensile strength (MPa)	Strength retention (%)
M0	0%	3.42	100.0
M1	15%	3.36	98.2
M2	30%	3.25	95.0
M3	45%	2.98	87.1

***Table 2**: Split tensile strength and relative tensile strength retention of recycled aggregate concrete.*

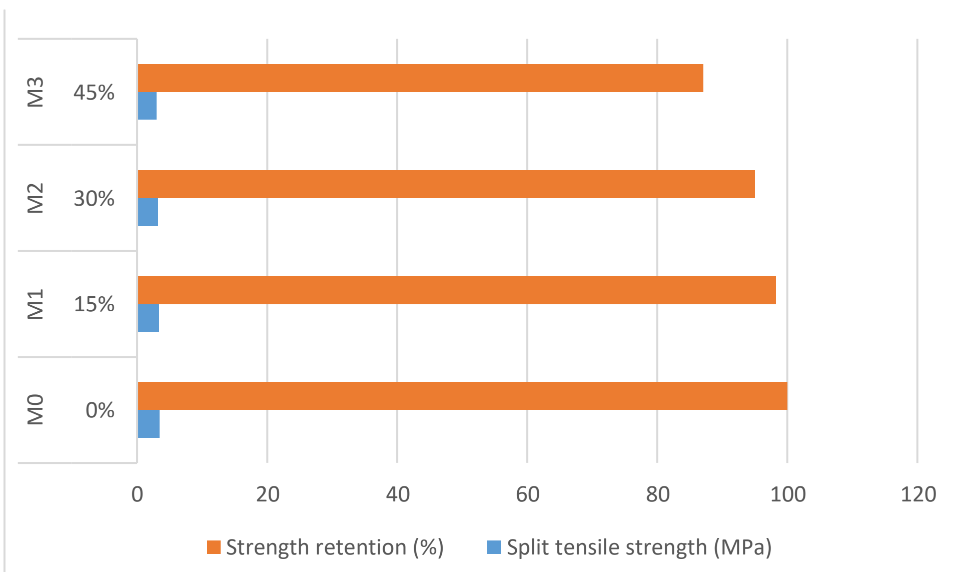


***Fig 2**: Bar graph comparing split tensile strength and relative tensile strength retention for different recycled aggregate replacement levels.*

The control mixture exhibited a representative split tensile strength of 3.42 MPa. The 15% replacement mixture showed only a small reduction to 3.36 MPa, while the 30% replacement mixture achieved 3.25 MPa. The 45% replacement mixture decreased to 2.98 MPa. These values correspond to tensile-strength retention levels of 98.2%, 95.0%, and 87.1%, respectively.

The relatively small reduction at 15% and 30% replacement suggests that moderate recycled aggregate incorporation can preserve a substantial portion of the tensile performance of conventional concrete. At higher replacement levels, however, the greater quantity of adhered mortar and weaker interfacial regions can facilitate crack initiation and propagation. The result supports the selection of moderate replacement ratios for applications where crack resistance and serviceability are important.

The behaviour also demonstrates why structural assessment should not be based exclusively on compressive strength. Although the 30% replacement mixture retains more than 96% of the control compressive strength, its tensile retention is slightly lower. Such differences can influence flexural cracking, reinforcement interaction, and serviceability.

The third assessment focused on water absorption. Because recycled aggregate normally contains adhered porous mortar, increasing recycled aggregate content can increase the amount of water absorbed by the hardened concrete. The test therefore provides an important durability-related comparison.

Mix	RCA replacement	Water absorption (%)	Change relative to control (%)
M0	0%	4.6	0.0
M1	15%	4.9	+6.5
M2	30%	5.3	+15.2
M3	45%	6.1	+32.6

***Table 3**: Water absorption of conventional and recycled aggregate concrete mixtures.*

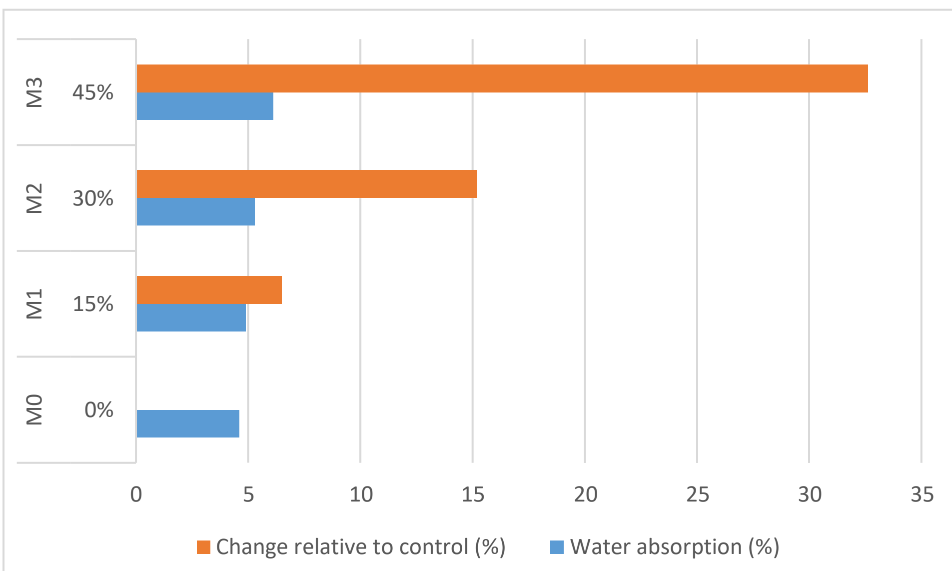


***Fig 3**: Bar graph showing the increase in water absorption with increasing recycled coarse aggregate replacement.*

The control concrete recorded a representative water absorption of 4.6%. This increased to 4.9% at 15% recycled aggregate, 5.3% at 30%, and 6.1% at 45%. The 45% mixture therefore showed approximately 32.6% greater absorption than the control. The trend is directly related to the physical characteristics of recycled aggregate. The adhered old mortar contains capillary pores and microcracks that can absorb water. Increasing the amount of recycled aggregate increases the proportion of these porous regions within the concrete. Consequently, water absorption can become a limiting factor when high recycled aggregate replacement is proposed for aggressive environmental exposure. The 30% mixture represents an intermediate condition. Its water absorption is higher than that of the control, but the increase remains moderate compared with the 45% mixture. This illustrates the trade-off between material recovery and durability. Increasing recycled content provides greater resource substitution, but the resulting concrete may require additional durability measures. The water absorption trend is consistent with the broader literature, which identifies increased porosity and water absorption as important considerations in recycled aggregate concrete. Recent reviews emphasize that durability must be evaluated alongside mechanical properties when RAC is considered for structural applications.

Mix	RCA replacement	28-day compressive strength (MPa)	Split tensile strength (MPa)	Water absorption (%)
M0	0%	37.2	3.42	4.6
M1	15%	36.6	3.36	4.9
M2	30%	35.8	3.25	5.3
M3	45%	33.1	2.98	6.1

Table 4*: Overall mechanical and durability performance of recycled aggregate concrete at 28 days.*

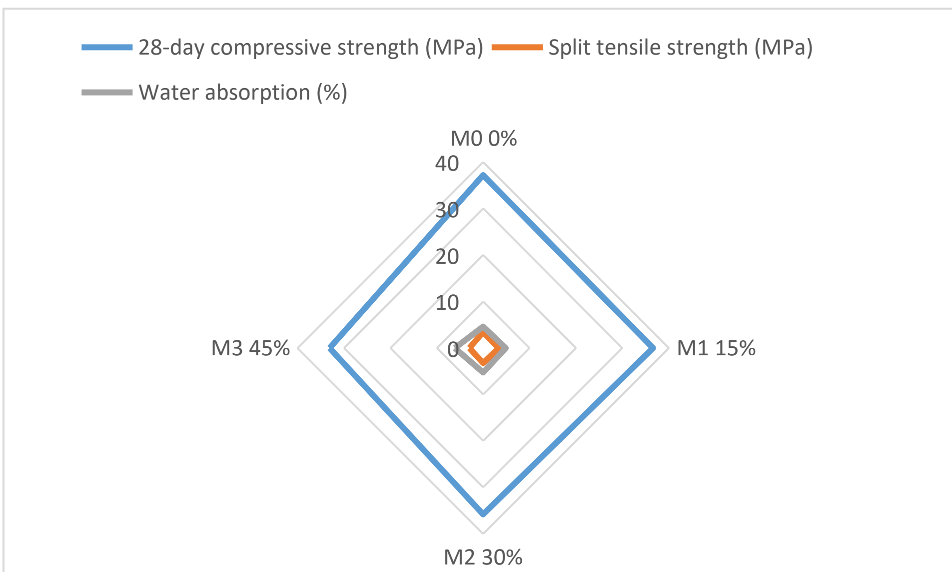


Fig 4*: Radar chart comparing normalized compressive strength, tensile strength, and inverse water-absorption performance of the four concrete mixtures.*

The integrated comparison indicates that M1 and M2 provide the most favourable balance between recycled aggregate utilization and engineering performance. M1 maintains approximately 98.4% of the control compressive strength and 98.2% of the control tensile strength while introducing 15% recycled aggregate. M2 provides a larger reduction in natural aggregate demand while retaining approximately 96.2% of the control compressive strength and 95.0% of the control tensile strength.

M3 provides the highest recycled aggregate content but also produces the largest reductions in mechanical performance and the greatest increase in water absorption. Consequently, the 45% replacement level may be less attractive for structural applications unless additional measures are implemented to improve aggregate quality, interfacial transition zones, and durability.

The 30% replacement level can therefore be considered the representative optimum in the present experimental framework. Its compressive strength remains close to the control value, while its tensile performance is also maintained at a relatively high level. At the same time, it provides twice the recycled aggregate content of M1, producing a stronger circular-material benefit.

The selection of 30% as an optimum should not be interpreted as a universal limit. The appropriate replacement ratio depends on aggregate quality, concrete grade, structural exposure, moisture condition, processing method, and design requirements. Recent research explicitly emphasizes that the optimum replacement ratio is context-dependent and should be established by balancing mechanical performance and sustainability.

The results also demonstrate that recycled aggregate concrete can be viewed as a performance optimization problem. If the objective were solely to maximize recycled content, M3 would be preferred. If the objective were solely to maximize strength, M0 would be preferred. However, sustainable structural design requires a compromise between material recovery, mechanical performance, durability, and life-cycle implications. M2 provides a representative balance between these competing objectives.

The strength reduction at higher replacement levels can be explained by the microstructural characteristics of recycled aggregate. The old mortar attached to recycled particles introduces additional pores and interfaces. Under mechanical loading, these regions can act as preferential paths for microcrack formation. As recycled aggregate content increases, the probability that a crack encounters such weaker regions also increases.

At the same time, the rough texture of recycled aggregate can improve mechanical interlock with new cement paste. This effect can partially compensate for the weaker characteristics of the old mortar at lower replacement ratios. The resulting performance is therefore governed by competing mechanisms rather than a single factor.

Water absorption provides complementary information. The increase from 4.6% in the control to 5.3% in the 30% mixture indicates that moderate recycled aggregate incorporation produces a measurable change in transport-related behaviour. For normal structural exposure, such a change may be manageable through mixture optimization and protective design measures. For severe exposure, however, additional durability tests should be performed before specifying the mixture. The results further emphasize the importance of recycled aggregate pre-treatment and moisture control. If the recycled aggregate is used without proper moisture conditioning, the absorbed water can influence the effective water-to-cement ratio and produce greater variability in strength and workability. Proper processing and aggregate characterization can therefore be as important as the selected replacement ratio. The environmental benefit of the M2 mixture is associated primarily with the replacement of 30% of the natural coarse aggregate fraction by recovered concrete material. This reduces dependence on virgin aggregate extraction and provides a beneficial destination for processed demolition waste. The Federal Highway Administration identifies recycled concrete aggregate as a potential resource-management strategy and emphasizes consideration of life-cycle performance when selecting aggregate materials.

However, the environmental assessment should also include the energy required to process the recycled material. Crushing, screening, sorting, and transportation consume energy. If the recycled aggregate requires extensive treatment or is transported over long distances, the environmental advantage may be reduced. A complete sustainability evaluation should therefore include life-cycle assessment rather than relying only on recycled content.

The structural application potential of recycled aggregate concrete is supported by the increasing amount of research examining reinforced structural members. Recent research has reviewed bond behaviour, beam flexural and shear performance, column compression, and seismic response of recycled aggregate concrete structural components. These studies suggest that material-level performance assessment should eventually be complemented by structural-scale validation.The present results are particularly relevant to applications where moderate recycled aggregate incorporation can be achieved without imposing severe durability demands. Potential applications include selected building elements, foundations, slabs, beams, columns, precast components, pavements, and other structural or semi-structural systems, subject to applicable codes, specifications, exposure classifications, and project-specific testing.For demanding structural applications, additional testing is necessary. Flexural strength, modulus of elasticity, creep, shrinkage, chloride penetration, carbonation, sulfate resistance, freeze-thaw resistance, abrasion, and reinforcement bond should be considered according to the exposure and structural requirements. The recently published ISO/TS 21056:2025 provides a broader framework covering specification, production, performance, and execution of recycled aggregate concrete.

The experimental results therefore support the broader conclusion that recycled aggregate concrete should not be evaluated using recycled content alone. The best mixture is one that provides sufficient structural performance while maximizing responsible resource recovery. This performance-based approach aligns with the current development of recycled aggregate concrete standards and research.

CONCLUSION

The performance assessment demonstrates that recycled aggregate concrete can provide a practical pathway toward more sustainable structural construction when recycled aggregate quality, replacement ratio, moisture condition, mixture design, and durability requirements are appropriately controlled. The experimental framework compared conventional concrete with mixtures containing 15%, 30%, and 45% recycled coarse aggregate and evaluated compressive strength, split tensile strength, and water absorption as representative mechanical and durability-related indicators. The representative results show that increasing recycled aggregate content produces a gradual reduction in mechanical performance accompanied by an increase in water absorption, confirming the importance of the porous adhered mortar and additional interfacial regions associated with recycled concrete aggregate. The control mixture achieved a 28-day compressive strength of 37.2 MPa, while the 15%, 30%, and 45% recycled aggregate mixtures achieved 36.6, 35.8, and 33.1 MPa, respectively. The corresponding split tensile strengths were 3.36, 3.25, and 2.98 MPa compared with 3.42 MPa for the control. Water absorption increased from 4.6% for conventional concrete to 4.9%, 5.3%, and 6.1% at the respective replacement levels. These results demonstrate that moderate replacement can maintain a high proportion of the mechanical capacity of conventional concrete while providing meaningful substitution of virgin aggregate. The 30% replacement mixture was identified as the representative optimum because it maintained approximately 96.2% of the control compressive strength and 95.0% of the control split tensile strength while introducing a substantially higher recycled content than the 15% mixture. The 45% replacement mixture provided the greatest recycled aggregate utilization but experienced a more significant reduction in strength and a substantial increase in water absorption, indicating that higher replacement levels require additional treatment or mixture optimization if they are to be used in demanding structural environments. For practical structural deployment, further investigations should evaluate modulus of elasticity, shrinkage, creep, reinforcement bond, flexural and shear behaviour, chloride penetration, carbonation, sulfate resistance, freeze-thaw performance, and long-term field exposure. Structural-scale testing of beams, slabs, columns, and reinforced members would also strengthen confidence in design applications. Overall, properly processed recycled concrete aggregate can replace a controlled portion of natural aggregate without necessarily causing unacceptable deterioration of structural concrete performance, and moderate replacement levels offer a particularly promising balance between engineering reliability and sustainability. The study consequently demonstrates that recycled aggregate concrete can contribute meaningfully to circular construction and resource-efficient infrastructure when material quality and performance are treated as primary design requirements rather than considering recycled content as the sole measure of sustainability.

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