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# Producing Concrete Incorporating Hybrid Cementitious Materials and Recycled Concrete Aggregate with Novel Thermal Treatment Methods

Wajde Shober Alyhya[1*], Awad Jadooe[1], Ghazwan A. Salman[2], Anmar Dulaimi[1,3], Mohammed N. Ahmed[1], Luís Filipe Almeida Bernardo[4]

[1] Department of Civil Engineering, Kerbala University, Kerbala, 56001, Iraq
[2] Contract Department, Ministry of Higher Education and Scientific Research, Baghdad, 10052, Iraq
[3] Civil Engineering and Built Environment School, Liverpool John Moores University, Liverpool L3 2ET, UK
[4] GeoBioTec, Department of Civil Engineering and Architecture, University of Beira Interior, 6201-001 Covilhã, Portugal
[*] Corresponding author, e-mail: wajde.alyhya@uokerbala.edu.iq

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**Abstract**

Recycled concrete aggregate (RCA), characterized by high porosity and adhered mortar, often impairs the mechanical strength and durability of concrete. This research develops a new integrated treatment method, which combines thermal-mechanical conditioning of RCA with hybrid supplementary cementitious materials (SCMs), including metakaolin (MK) and ground granulated blast-furnace slag (GGBS). Three thermal treatment protocols were applied to enhance RCA quality, and concrete mixes with 50% and 100% RCA replacement were prepared. The study investigated the impact of adding MK up to 30% and GGBS up to 20% on the compressive strength, splitting tensile strength, workability, and water absorption of concrete. Although isolated effects require further investigation, the research found that the integrated use of TT3-treated RCA, where TT3 refers to the stepped thermal treatment protocol and SCMs, showed promising performance under the experimental conditions, producing a 90-day compressive strength greater than that of the control mix and reducing water absorption by more than 30%. The combined application of thermal-mechanical treatment (TT3) on RCA and the use of hybrid supplementary cementitious materials (SCMs), such as metakaolin (MK) and ground granulated blast-furnace slag (GGBS), significantly improved the concrete properties. The integrated use of TT3-treated RCA and SCMs resulted in a 90-day compressive strength that was 5.5% higher than that of the control mix, indicating significant long-term performance improvements.

**Keywords**

residual mortar, hybrid cementitious binders, recycled concrete aggregate (RCA), aggregate replacement ratios, thermal conditioning treatments

## 1 Introduction

Regardless of the cause, the construction industry remains a major consumer of energy and raw materials, contributing significantly to environmental pollution and greenhouse gas emissions. The ever-increasing demand for concrete, driven by fast infrastructure development, has exacerbated the unsustainable exploitation of natural resources, particularly aggregates and cement [1]. Currently, the accumulation of construction and demolition (C&D) waste is becoming a conservation concern, with projections estimating that volumes will exceed 2.2 billion tons annually by 2025 [2]. In the same regard, the production of Portland cement alone accounts for approximately 8% of global anthropogenic $CO_2$ emissions, highlighting the urgent need for more sustainable construction alternatives [3]. Recycled concrete aggregates (RCA), derived from crushed concrete debris, provide a promising alternative to natural aggregates. Their use can substantially reduce both the demand for virgin aggregates and the burden of construction and demolition (C&D) waste, which is projected to exceed 2.2 billion tons annually by 2025 [4, 5]. However, limitations persist regarding their application in structural concrete, primarily due to inferior properties compared to natural aggregates. These issues are attributed mainly to the presence of adhered mortar, which increases porosity and water absorption, reduces specific gravity, and weakens the interfacial transition zone (ITZ) between the cement paste

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and aggregate [6–8]. Consequently, concrete made with RCA often exhibits reduced strength and durability [9, 10].

Various treatment methods – including mechanical, chemical, and thermal approaches – have been explored to mitigate these drawbacks [11–13]. The purpose of these treatments was to improve the mechanical and physical properties of RCA by reducing or eliminating the adhering mortar [14–18]. Notably, RCA introduces two distinct ITZs in concrete: one between the original aggregate and the residual mortar, and another between the residual mortar and the new cement matrix (Fig. 1) [2]. In contrast, natural aggregates form only a single ITZ, which generally promotes better matrix cohesion.

Techniques for enhancing RCA quality include chemical treatments such as carbonation and acid soaking [19]. However, due to their high cost, complicated waste disposal requirements, and toxicity, these methods pose significant environmental and safety risks. Physical treatments, such as abrasion and grinding, are also commonly used to remove adhered mortar. While effective, these methods are energy-intensive and risk damaging the aggregate structure. On the other hand, thermal treatment involves the application of controlled heating to weaken the bond between the adhered mortar and the aggregate, thus facilitating mechanical separation. Despite its potential, research on energy-efficient and scalable thermal treatment protocols remains in early stages, particularly regarding cyclic and stepped heating approaches.

Furthermore, supplementary cementitious materials (SCMs) have emerged as a promising technology for enhancing both the performance and sustainability of concrete, thereby expanding the understanding and application of modern concrete. SCMs such as fly ash, silica fume, slag, and metakaolin have been widely used

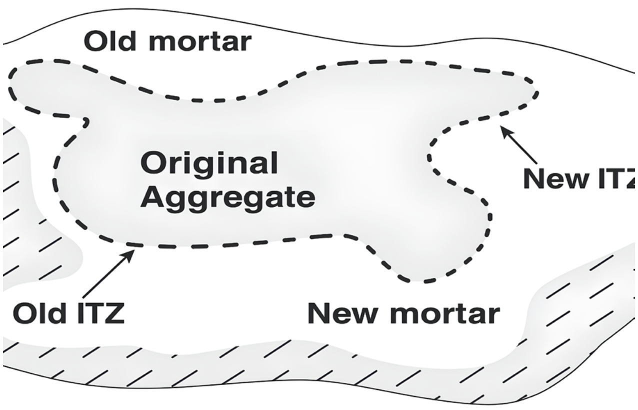


**Fig. 1** Aggregate–mortar microstructure schematic (adapted from [2])

to partially replace Portland cement, delivering benefits that extend beyond reduced carbon emissions to include improved workability, mechanical strength, and long-term durability [19–21]. When combined with RCA, SCMs can mitigate their inherent drawbacks by refining the concrete microstructure and enhancing the ITZ [22, 23]. Among the high-reactivity pozzolans, metakaolin (MK) and ground granulated blast-furnace slag (GGBS) have demonstrated notable efficiency, contributing to strength enhancement and improved durability performance [24].

Although recycled concrete aggregates (RCA) have been increasingly studied as a sustainable alternative to natural aggregates, challenges remain regarding their variable quality, residual mortar content, and resulting reductions in mechanical performance. Recent studies have explored thermal, mechanical, and chemical treatments to enhance RCA properties, but most approaches rely on high-energy processes or treat aggregates in isolation. Furthermore, most existing studies on thermal treatment apply excessively high temperatures (above 300 °C), which limits the practical implementation and commercialization of this approach [25, 26]. To address these limitations, the present study investigates a combined approach that integrates three low-energy thermal treatments (TT1, TT2, and TT3) with mechanical abrasion of the recycled concrete aggregates to enhance their properties. In addition, a hybrid system of supplementary cementitious materials (metakaolin and GGBS) is employed to reduce cement consumption while improving the overall performance of the concrete.

To address these limitations, the present study investigates a combined approach that integrates three low-energy thermal treatments (TT1, TT2, and TT3) with mechanical abrasion of the recycled concrete aggregates to enhance their properties. Indeed, a hybrid system of supplementary cementitious materials (metakaolin and GGBS) is employed to reduce cement consumption while improving the overall performance of the concrete. The proposed approach involves mechanical enhancement and sustainability, grounding the work within the circular construction scheme. The main objectives of this study include:

- Evaluate the effect of different low-temperature thermal treatment protocols (TT1, TT2, and TT3) on RCA performance.
- Investigate the synergistic interaction between thermally treated RCA and high-volume SCMs replacement (MK + GGBS).
- Compare mechanical properties and durability indicators across concrete mixes with 50% and 100% RCA replacement.

- Assess the feasibility of using treated RCA and ternary binders in producing durable, eco-efficient concrete for structural applications.

These contributions aim to support sustainable concrete practices by providing a pathway for the large-scale use of RCA with improved performance and a reduced carbon footprint. Although this work investigates the combined use of RCA treatment and SCM integration, future research is needed to isolate their contributions through factorial experimental designs. The novelty of this study lies in combining low-energy stepped thermal treatment with mechanical abrasion and a tailored hybrid SCM system (MK and GGBS). This integrated approach has not been previously reported and provides new insights into enhancing RCA performance while reducing cement demand.

## 2 Experimental program

To assess the effectiveness of three thermal treatment protocols and mechanical abrasion in improving the properties of RCA, this study employs a structured experimental program. It further examines the combined effects of these treatments, along with hybrid SCMs, on the overall performance of concrete. The methodology encompasses material characterization, RCA processing, concrete mix design, sample preparation, curing, and a comprehensive assessment of both fresh and hardened concrete properties.

### 2.1 Materials sourcing and characterization

#### 2.1.1 Ordinary Portland cement

The primary cementitious binder utilized in this study was locally sourced ordinary Portland cement (OPC), which complies with Iraqi Standard No. 5:2019. The chemical and physical characteristics of the OPC are presented in Tables 1 and 2, respectively.

#### 2.1.2 Supplementary cementitious materials: MK and GGBS

Two types of SCMs were used in this study: MK, selected for its high pozzolanic activity, and GGBS, selected for its latent hydraulic properties.

- Metakaolin (MK) is a calcined, high-purity kaolinitic clay produced by thermal activation at 500–800 °C. The MK used in this work exhibits high pozzolanic activity, contributing to the formation of secondary calcium silicate hydrate (C–S–H) and producing alumina-rich phases, such as $C_4AH_{13}$, $C_2ASH_8$, and $C_3AH_6$ [27–29]. The material consists of 99.9% of its particles with a particle size below 16 µm, with an average of 3 µm. Detailed chemical and physical characteristics are provided in Tables 3 and 4.
- Ground granulated blast-furnace slag (GGBS) is an industrial by-product of iron production, processed to a fine powder and conforming to ASTM C989/C989M-18a [30]. GGBS exhibits both hydraulic and pozzolanic properties, thereby enhancing its long-term strength and durability. Its composition and fineness are given in Tables 3 and 4.

**Table 1** Chemical composition of OPC

| Components (%) | Test results | Iraqi standard limits (No. 5/ 2019) |
|---|---|---|
| CaO | 61.52 | - |
| $SiO_2$ | 20.35 | - |
| $Al_2O_3$ | 4.810 | - |
| $Fe_2O_3$ | 3.510 | - |
| MgO | 2.270 | ≤ 5.0 |
| $SO_3$ | 1.590 | ≤ 2.8 % if $C_3A$ ≥ 5% |
| $Na_2O$ | 0.350 | |
| $K_2O$ | 0.400 | |
| L.S.F | 0.930 | 0.66–1.20 |
| Insoluble Residue (IR) | 0.440 | ≤ 1.5 |

**Table 2** Physical properties of OPC

| Tests | | Test results | Iraqi standard limits (No. 5/ 2019) |
|---|---|---|---|
| Fineness (Blaine), ($m^2$/kg) | | 325 | ≥ 235 |
| Initial setting time (min) | | 127 | ≥ 45 |
| Final setting time (min) | | 207 | ≤ 600 |
| Compressive strength (MPa) | (2 days) | 21.9 | ≥ 20.0 |
| | (28 days) | 46.2 | ≥ 42.5 |

**Table 3** Chemical composition of MK and GGBS

| Component (%) | Test results | |
|---|---|---|
| | MK | GGBS |
| $SiO_2$ | 52.0 | 37.5 |
| $Al_2O_3$ | 39.3 | 6.40 |
| $Fe_2O_3$ | 1.80 | 0.51 |
| CaO | 1.80 | 34.6 |
| MgO | 0.15 | 8.60 |
| $Na_2O$ | 0.07 | 0.38 |
| $K_2O$ | 0.30 | - |
| $SO_3$ | 0.00 | - |
| $TiO_2$ | 2.30 | - |

**Table 4** Physical properties of MK and GGBS

| Property | Test results | |
|---|---|---|
| | MK | GGBS |
| Colour | Off-white | Light grey |
| Physical form | Powder | Powder |
| Specific gravity | 2.50 | 2.76 |
| Bulk density ($g/cm^3$)* | 0.35 to 0.50 | 1.25 |
| Fineness modulus ($cm^2/g$) | - | 4100 |

* Note: 'Bulk density' is retained as the standard term to describe the mass per unit volume of the powdered material, measured including voids between particles.

### 2.1.3 Natural Sand (NS)

The natural sand used in this study was a locally sourced, well-graded natural sand that conforms to the requirements of the Iraqi Standard No. 45:1984 [31]. It has a maximum particle size of 4.75 mm and was used in the preparation of all concrete mixes. Its particle size distribution was determined according to ASTM C136/C136M-23 [32], while specific gravity and water absorption were measured in accordance with ASTM C127-24 and ASTM C128-12, respectively [33, 34]. The grading and physical properties of the natural sand are summarised in Tables 5 and 6.

### 2.1.4 Natural coarse aggregate (NCA)

The natural coarse aggregate (NCA) used in this study was a locally available crushed stone with a nominal maximum size of 20 mm. It was selected based on its compliance with the Iraqi standard specification No. 45:1984 [31] for aggregates used in concrete. The grading, chemical, and physical properties of NCA were evaluated and are presented in Tables 6 and 7. The aggregate grading was assessed in accordance with ASTM C136/C136M-23 [32].

**Table 5** Grading of NS

| Sieve opening (mm) | Passing(%) |
|---|---|
| 4.75 | 100 |
| 2.36 | 89.8 |
| 1.18 | 80.0 |
| 0.60 | 66.9 |
| 0.30 | 37.9 |
| 0.15 | 3.60 |

**Table 6** Physical properties of NS, NCA, and RCA

| Property | NS | NCA | RCA* |
|---|---|---|---|
| Specific gravity | 2.596 | 2.650 | 2.420 |
| Water absorption (%) | 1.850 | 0.550 | 5.710 |
| Sulfate content ($SO3\%$) | 0.210 | 0.075 | - |

* Note: The water absorption value shown here refers to untreated RCA. For the water absorption performance of concrete using thermally treated RCA.

**Table 7** Grading of NCA

| Sieve opening (mm) | Passing(%) |
|---|---|
| 19.0 | 100 |
| 14.0 | 95.0 |
| 9.50 | 76.0 |
| 4.75 | 8.00 |

### 2.1.5 Recycled concrete aggregate (RCA)

The RCA used in this study was obtained by crushing waste concrete specimens, specifically tested cubes collected from a local laboratory, to ensure the material originated from mature, uncontaminated concrete. The crushed material was processed through sieving to isolate coarse fractions, ensuring consistency with the grading of natural coarse aggregate (NCA) for accurate concrete mix design. The physical properties of RCA, including specific gravity and water absorption, were determined and are presented in Table 6. The use of treated RCA in this study aims to evaluate its performance when integrated into structural-grade concrete, combined with thermal and mechanical treatments.

### 2.1.6 Water

Potable tap water, free from impurities and conforming to ASTM C1602/C1602M-22 [35] requirements for concrete mixing and curing, was used throughout the study. This water ensured that no adverse chemical interactions occurred with the cementitious components and aggregates, thereby maintaining the integrity of the hydration process and the overall concrete performance.

### 2.1.7 Chemical admixtures (Superplasticiser)

A polycarboxylic ether superplasticizer (SP) was used to prepare all mixes, conforming to ASTM C494/C494M-24 [36], as needed to meet the targeted workability requirements. Its type and dosage were carefully selected and administered according to the manufacturer's specifications.

## 2.2. Treatment of recycled concrete aggregate

Initially, mature and uncontaminated concrete cubes were collected and mechanically crushed to obtain particle sizes smaller than 50 mm. The crushed material was then sieved to separate fine and coarse fractions according to standard grading requirements. The coarse RCA samples were subjected to low-temperature thermal treatment, followed by mechanical abrasion using a Los Angeles abrasion device (without steel balls) for 10 minutes to remove loosened adhered mortar. The treated RCA was compared to a control group (untreated RCA) and exposed to the following dry heating thermal treatment protocols:

- Thermal Treatment 1 (TT1): Single-cycle heating at 200 °C for 2 h, followed by natural air cooling at ambient conditions.
- Thermal Treatment 2 (TT2): A three-cycle heating protocol, each consisting of 2 h at 200 °C followed by 6 hours of natural air cooling between cycles.
- Thermal Treatment 3 (TT3): A stepped heating procedure comprising three stages: heating at 100 °C, 200 °C, and 300 °C sequentially, each sustained for 2 h before proceeding to the next, ending with air cooling. In other words, TT3 involves heating RCA to the target temperature in three consecutive steps, with a 120-minute holding time at each step to ensure uniform heating, followed by gradual cooling to room temperature. Mechanical abrasion was applied immediately after the final cooling stage to remove loosely attached mortar and enhance aggregate surface characteristics before mixing with cementitious materials.

### 2.2.1 Thermal treatment procedure

The RCA samples were thoroughly washed with distilled water to remove surface contaminants and then air-dried to achieve uniform moisture content. For thermal treatment, the dried aggregates were spread in a single layer on ceramic trays and placed in a programmable laboratory oven. Heating was carried out at a controlled rate of 20 °C/min, reaching a maximum temperature of 200 °C, as described in the previously outlined treatment protocols (TT1, TT2, and TT3). After thermal exposure, the RCA was allowed to cool naturally to room temperature inside the oven, followed by mechanical abrasion in a Los Angeles abrasion machine (without steel balls) to remove loosened mortar. The treated RCA was then stored in airtight polyethylene containers to prevent moisture uptake prior to use. The thermal treatment procedure was conducted following the steps below:

- Oven Setup: Preheat the programmable laboratory oven to a stable and uniform temperature distribution, with a maximum set point of 200 °C.
- Heating Rate: Arrange the RCA in heat-resistant ceramic trays in a single layer to ensure uniform exposure to heat. Increase the temperature at a rate of 20 °C/min until the target temperature is reached.
- Holding Time: Once the target temperature is reached, maintain the required duration according to the specific thermal treatment, ensuring temperature stability using the oven's internal sensor.
- Cooling Phase: After completion of the heating cycle, turn off the oven and allow the RCA to cool gradually to room temperature within the closed chamber.
- Replication: Repeat the thermal procedure for each treatment protocol under its respective conditions to ensure experimental consistency.

Thermal treatment protocols (TT1, TT2, and TT3) are designed with practical and environmental considerations in mind, as opposed to most high-temperature treatments that exceed 300 °C. The selected temperature range (100–300 °C) meets the goals of minimizing adhered mortar, enhancing RCA surface quality, and yet maintaining the mechanical integrity of aggregates. TT1 represents an elementary single cycle at 200 °C for 2 h, which serves as a reference for the minimum single intervention. At the same time, TT2 involves the application of three heating and cooling cycles, modelled as thermal fatigue effects and cyclic stress redistributions, inspired by passive thermal exposure, such as precast concrete elements left in unshaded environments in hot regions. TT3 employs a stepped heating regime (100 °C → 200 °C → 300 °C) to achieve progressive thermal ramping conditions that can be developed in either drying sheds or surface-heated storage conditions, allowing for gradual moisture loss and matrix relaxation without thermal shock. They are also resource-conserving and low-energy alternatives to conventional thermal methods, enabling more sustainable production of concrete. Finally, this may be readily dismissed as extreme laboratory-induced damage rather than likely paralysis in field-adjacent thermal exposures. Thus, relevant literature also supports this (e.g., [11, 18, 37, 38]). The selection of stepped and cyclic thermal treatments (TT1, TT2, and TT3) reflects exploratory protocols rather than field-validated conditions. These serve to investigate potential aggregate surface improvements under controlled environments but require further validation.

### 2.2.2 Post-treatment handling and storage

After thermal treatment, the RCA samples were allowed to cool before being carefully removed from the oven. Once cooled, the TT3-treated aggregates were subjected to mechanical abrasion using the Los Angeles apparatus (without steel balls) for the specified duration to remove loosened mortar. After abrasion, the fine particles generated were sieved through a 4.75 mm sieve, ensuring that only the coarse fraction of RCA was retained. This step prevents the fines from adhering to the aggregate surface, which could negatively affect adhesion with the cement matrix and the resulting mechanical properties. The treated RCA was then stored in sealed, airtight polyethylene containers to prevent moisture absorption prior to use. All containers were clearly labelled according to their respective treatment conditions to ensure traceability during the mix design and testing process. The treated RCA was then considered ready for incorporation into concrete mixes, following the experimental design, to assess its effects on the fresh and hardened properties of concrete, particularly when used in combination with hybrid supplementary cementitious materials (SCMs).

### 2.3 Concrete mix design

Concrete mixes were prepared according to the principles of standardized mix design procedures, supported by preliminary trial batches that targeted a slump of 75 ± 15 mm and a water-to-cementitious materials ratio (w/cm) of 0.45. To maintain a consistent total cementitious material composition in all mixes, RCA replacement levels of 50% and 100% by weight of NCA were employed. The mix proportions per cubic meter of concrete are provided in Table 8. A total of twenty-one experimental mix combinations (in addition to the control mix) were developed to incorporate variations in SCMs content, RCA treatment protocols, and replacement levels, as detailed in Table 9. The selection of experimental variables was based on both scientific rationale and practical feasibility. As an energy-efficient threshold, a thermal treatment temperature of 200 °C was selected, which is significantly lower than the temperature at which cement hydration products decompose. Cyclic heating (TT2) and stepped heating (TT3) were employed to simulate realistic field conditions and evaluate the impact of different thermal regimes on RCA properties. To ensure the practical application of the suggested mix designs, the replacement percentages of SCMs were chosen within widely recognized ranges documented in the literature. This methodology provides a systematic and robust framework for evaluating how the integration of treated RCA and hybrid SCMs affects the fresh and hardened performance of concrete, with a view toward sustainable and structurally viable applications in the construction industry.

**Table 8** Concrete mix proportion (kg/m$^3$)

| Constituent | Quantity |
|---|---|
| Cement | 400 |
| Natural sand (NS) | 840 |
| Natural coarse aggregate (NCA) | 865 |
| w/c % | 0.45 |
| Superplasticizer | 1.2 l/100 kg cement |
| Slump (mm) | 75 ± 15 |

**Table 9** Detailed experimental work

| Mix ID | RCA level (%) | RCA treatment | OPC (%) | MK (%) | GGBS (%) |
|---|---|---|---|---|---|
| Control-100NCA | 0 | | | | |
| 50NCA+50RCA | 50 | None | 100 | 0 | 0 |
| 0NCA+100RCA | 100 | | | | |
| HCM-50-TT1-A | 50 | | 60 | 20 | 20 |
| HCM-50-TT1-B | 50 | TT1 | 55 | 25 | 20 |
| HCM-50-TT1-C | 50 | | 50 | 30 | 20 |
| HCM-50-TT2-A | 50 | | 60 | 20 | 20 |
| HCM-50-TT2-B | 50 | TT2 | 55 | 25 | 20 |
| HCM-50-TT2-C | 50 | | 50 | 30 | 20 |
| HCM-50-TT3-A | 50 | | 60 | 20 | 20 |
| HCM-50-TT3-B | 50 | TT3 | 55 | 25 | 20 |
| HCM-50-TT3-C | 50 | | 50 | 30 | 20 |
| HCM-100-TT1-A | 100 | | 60 | 20 | 20 |
| HCM-100-TT1-B | 100 | TT1 | 55 | 25 | 20 |
| HCM-100-TT1-C | 100 | | 50 | 30 | 20 |
| HCM-100-TT2-A | 100 | | 60 | 20 | 20 |
| HCM-100-TT2-B | 100 | TT2 | 55 | 25 | 20 |
| HCM-100-TT2-C | 100 | | 50 | 30 | 20 |
| HCM-100-TT3-A | 100 | | 60 | 20 | 20 |
| HCM-100-TT3-B | 100 | TT3 | 55 | 25 | 20 |
| HCM-100-TT3-C | 100 | | 50 | 30 | 20 |

### 2.4. Mixing and casting procedures

The concrete ingredients were mixed in a laboratory drum mixer according to ASTM C192/C192M-07 [39]. The procedure began with dry mixing of aggregates and binders for 2 minutes, followed by the gradual addition of water over a maximum period of 3 minutes. After the addition of water, the mix was allowed to rest for 2 minutes, then remixed for an additional 2 minutes to ensure homogeneity and reduce variability. This standardized mixing sequence and timing were consistently applied to all mix combinations. Fresh concrete was then cast into molds in three layers, with each layer compacted using vibration for a predetermined period to minimize air voids and ensure uniform density. All specimens were labelled correctly according to their mix designation and treatment conditions for traceability during testing.

**2.5 Curing regime**

All cast specimens will be demolded after 24 ± 2 h and placed into a controlled curing regime in a water tank, in an environment with relative humidity values above 95% and at a room temperature of 20 ± 1 °C, until the defined testing ages of one week, 4 weeks, and approximately thirteen weeks.

**2.6 Testing of fresh and hardened concrete properties**

A slump test was conducted following ASTM C143/C143M-20 [40] immediately after mixing to evaluate the workability of fresh concrete. Concrete specimens were cast in clean, oiled molds of standardized dimensions for various tests. These included:

- Cubes (100 × 100 × 100 mm) for compressive strength and water absorption tests.
- Cylinders (100 mm diameter × 200 mm height) for the indirect splitting tensile strength test (Brazilian test).

For each test type and curing age, a minimum of three specimens per mix were tested, and the average value was reported to ensure reliability and statistical validity of the results. A factorial experimental design was employed to systematically investigate the influence of key variables on both the fresh and hardened properties of concrete.

**3 Results and discussion**

**3.1 Slump test**

The slump results for all mixes are summarised in Table 10 and Fig. 2. The control mix (Control-100NCA), which consisted of 100% NCA and OPC, exhibited the highest slump (80 mm), indicating optimal workability. For the HCM-50 series (50% RCA), a slight reduction in the slump was observed across all treatments. TT1 mixes showed decreasing slump with higher MK content, from 72 mm (TT1-A) to 67 mm (TT1-C), highlighting the influence of MK in reducing workability due to its high surface area and water demand. TT2, on the other hand, produced slightly higher slump values, while TT3 yielded the best workability, with HCM-50-TT3-A achieving a slump of 76 mm, which is close to the control. In the HCM-100 series (100% RCA), slump values dropped further due to the complete replacement of NCA. The lowest value was recorded for HCM-100-TT1-C (64 mm), whereas TT2 and TT3 again showed improvements, with TT3-A achieving 74 mm, nearly comparable to 50% RCA mixes. Overall, TT3 consistently improved RCA surface properties, enhancing workability across mix types, while MK content remained the primary factor reducing slump.

Across all mixes, increasing MK content consistently reduced slump, owing to its high fineness and water demand. However, this adverse effect was mitigated by thermal treatment, particularly TT3, which improved aggregate surface texture and reduced water absorption. The enhanced workability observed in TT3-treated mixes may be attributed to improved aggregate quality, as indicated by reduced water absorption (which will be discussed later); however, the role of superplasticizer dosage – especially in mixes with higher SCMs content – may also contribute to this effect. Among the three thermal treatments, the TT3 treatment, which combines ternary SCMs integration, resulted in the highest performance observed. This suggests a potential synergistic interaction, though the individual contributions cannot be wholly decoupled under the current design.

In contrast, TT1 and TT2 were less successful in offsetting the workability loss associated with increased MK. Interestingly, this outcome is consistent with earlier studies involving natural coarse aggregates [41]. While TT3 generally improved the slump relative to TT1 and TT2, the results were not entirely consistent across all binder combinations. This variability may stem from the interaction between the RCA surface condition (influenced by thermal treatment), the moisture state of adhered mortar, and the specific demands of the ternary binder system (Table 11). TT2, in particular, may cause irregular microstructural changes due to cyclic thermal stresses, which can affect water absorption in ways not entirely predictable from surface appearance alone.

**3.2. Compressive strength**

The compressive strength test was performed at 7, 28, and 90 days for all concrete mixes, as shown in Fig. 3. The results demonstrated a progressive strength development over time, with the plotted curves showing typical behavior for the control mix and varying degrees of early-age strength retardation in the HCM-based mixes, followed by enhanced long-term strength development.

The control mix (Control-100NCA), which contains 100% NCA and no SCMs, exhibited the highest baseline strength across all ages, reaching 34 MPa at 7 days, 44 MPa at 28 days, and 52 MPa at 90 days. On the other hand, experimental mixes incorporating hybrid cementitious materials (HCMs) – including MK and GGBS – were grouped into the HCM-50 and HCM-100 series, representing 50% and 100% replacement of RCA, respectively. These mixes exhibited variable early-age strengths, often slightly lower than those of the control, but many achieved comparable or

**Table 10** Slump values for all mixes

| Mix ID | RCA level (%) | RCA treatment | OPC (%) | MK (%) | GGBS (%) | Slump (mm) | Remarks |
|---|---|---|---|---|---|---|---|
| Control-100NCA | 0 | | 100 | 0 | 0 | 80 | The highest slump due to natural aggregates and no SCM |
| 50NCA+50RCA | 50 | None | 100 | 0 | 0 | 76 | Moderate reduction due to RCA |
| 0NCA+100RCA | 100 | | 100 | 0 | 0 | 70 | More reduction due to high RCA |
| HCM-50-TT1-A | 50 | | 60 | 20 | 20 | 72 | Moderate reduction due to MK; TT1 moderately improves RCA surface |
| HCM-50-TT1-B | 50 | TT1 | 55 | 25 | 20 | 70 | More MK slightly reduces the slump further |
| HCM-50-TT1-C | 50 | | 50 | 30 | 20 | 67 | The highest MK leads to the lowest slump in the TT1 group |
| HCM-50-TT2-A | 50 | | 60 | 20 | 20 | 74 | TT2 enhances RCA quality and slightly improves workability |
| HCM-50-TT2-B | 50 | TT2 | 55 | 25 | 20 | 72 | Acceptable slump with improved aggregate and SCM balance |
| HCM-50-TT2-C | 50 | | 50 | 30 | 20 | 70 | Still within an acceptable range |
| HCM-50-TT3-A | 50 | | 60 | 20 | 20 | 76 | The best RCA treatment leads to the best workability among RCA mixes |
| HCM-50-TT3-B | 50 | TT3 | 55 | 25 | 20 | 74 | Slightly reduced due to more MK |
| HCM-50-TT3-C | 50 | | 50 | 30 | 20 | 72 | High MK, but TT3 maintains an acceptable Slump |
| HCM-100-TT1-A | 100 | | 60 | 20 | 20 | 68 | Lower slump due to full RCA and high MK |
| HCM-100-TT1-B | 100 | TT1 | 55 | 25 | 20 | 66 | Approach the lower limit of the target range |
| HCM-100-TT1-C | 100 | | 50 | 30 | 20 | 64 | Borderline acceptable, may require superplasticizer |
| HCM-100-TT2-A | 100 | | 60 | 20 | 20 | 70 | Slight improvement due to better RCA behavior |
| HCM-100-TT2-B | 100 | TT2 | 55 | 25 | 20 | 68 | Still within an acceptable range |
| HCM-100-TT2-C | 100 | | 50 | 30 | 20 | 66 | Low but workable with proper mixing and admixtures |
| HCM-100-TT3-A | 100 | | 60 | 20 | 20 | 74 | TT3 provides the best slump recovery at 100% RCA |
| HCM-100-TT3-B | 100 | TT3 | 55 | 25 | 20 | 72 | Good balance between SCM and RCA effects |
| HCM-100-TT3-C | 100 | | 50 | 30 | 20 | 70 | Best performance among complete RCA mixes with high SCM |

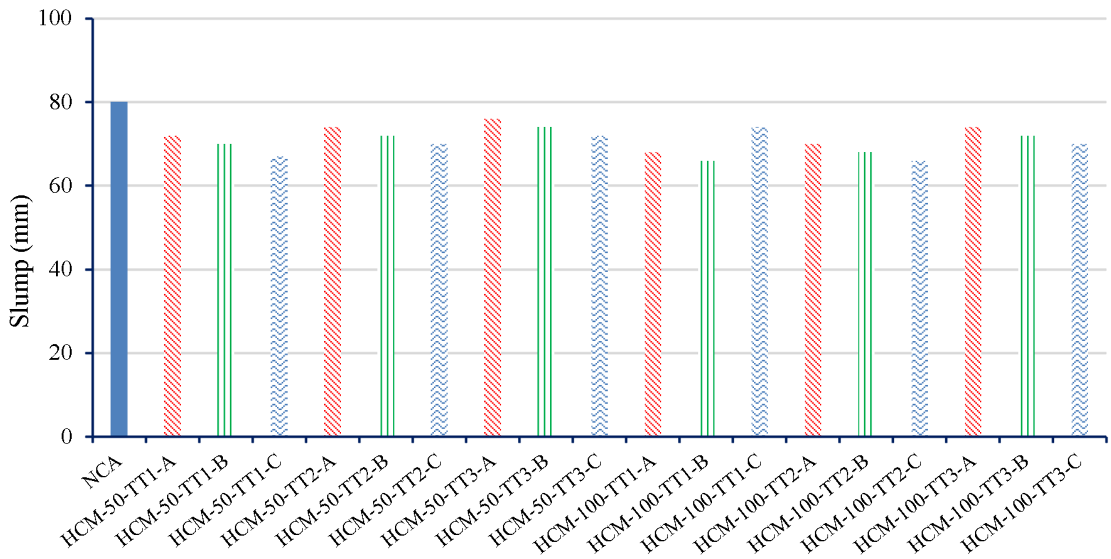


**Fig. 2** Impact of thermal treatment on slump values at different RCA contents with hybrid SCMs

superior 90-day strengths. Although RCA typically exhibits lower quality and higher porosity, the superior performance of mixes such as HCM-100-TT3-C can be attributed to the combined effects of TT3 treatment, which improves aggregate-matrix bonding, and the enhanced pozzolanic activity of MK and GGBS. This appears to offset the negative impact of complete RCA replacement, resulting in strength values comparable to or even exceeding the control mix at later ages. For example, HCM-50-TT3-C achieved 35 MPa (7 days), 46 MPa (28 days), and 55 MPa

**Table 11** Qualitative summary of hypothesized factors influencing slump variability across thermal treatment protocols

| Factor | TT1 | TT2 | TT3 |
|---|---|---|---|
| Mortar removal consistency | Low | Moderate (cyclic fatigue) | High (progressive heating) |
| Surface roughness | Moderate | Variable | Uniform |
| Water absorption behavior | High | Inconsistent (cyclic drying/ shrinkage) | Controlled (gradual dehydration) |
| Slump response (general) | Lower | Variable | Slightly more stable |

Note: This table presents expected trends based on observed workability results and known effects of thermal processing from the literature. Parameters such as surface roughness and absorption behavior were inferred rather than directly measured.

(90 days), surpassing the control at later ages. This performance illustrates the combined benefits of TT3 thermal treatment and optimal SCM replacement levels.

In contrast, the HCM-100 series generally showed lower early and long-term strengths. The reason the filler and pozzolanic effect appear in the later ages, rather than in the early ages, is due to the development of strength. For instance, HCM-100-TT1-A reached only 28 MPa at 7 days. However, specific mixes in this group exhibited strength gains over time. Notably, HCM-100-TT3-C reached 53 MPa at 90 days, closely matching the control mix, despite using 100% RCA as the binder. Among the thermal treatments, TT3 consistently delivered the best strength results across both RCA replacement levels. This is attributed to TT3's ability to improve aggregate surface quality and reduce porosity, thereby enhancing the bond between the aggregate and the cementitious matrix. Both HCM-50-TT3-B and HCM-50-TT3-C, which used 50% RCA, 25–30% MK, and 20% GGBS, produced compressive strengths at 90 days that were comparable to or slightly higher than those of the control. These results highlight the synergistic effects of MK and GGBS, where MK contributed through its extended pozzolanic activity and filler effect, and GGBS improved long-term strength through pore refinement.

Overall, thermal treatment, particularly TT3, successfully counteracted the decrease in compressive strength as the RCA concentration increased. The highest 90-day strength values were found in the 30% MK mixes, such as HCM-50-TT3-C and HCM-100-TT3-C, among their respective groups. This suggests that TT3 treatment, combined with increased MK content, provides significant long-term performance improvements.

### 3.3 Splitting tensile strength

The splitting tensile strength results for concrete mixes incorporating 0%, 50%, and 100% RCA, treated using three different surface modification methods (TT1, TT2, and TT3), in combination with SCMs, are presented in Fig. 4. Strength measurements were conducted at 7, 28, and 90 days, capturing both early and long-term performances. The trends observed were generally consistent with those found in the compressive strength tests.

Using only NCA and OPC, the control mix (Control-100NCA) produced the highest tensile strength values across all age groups, as anticipated: 3.1, 4.2, and 4.6 MPa

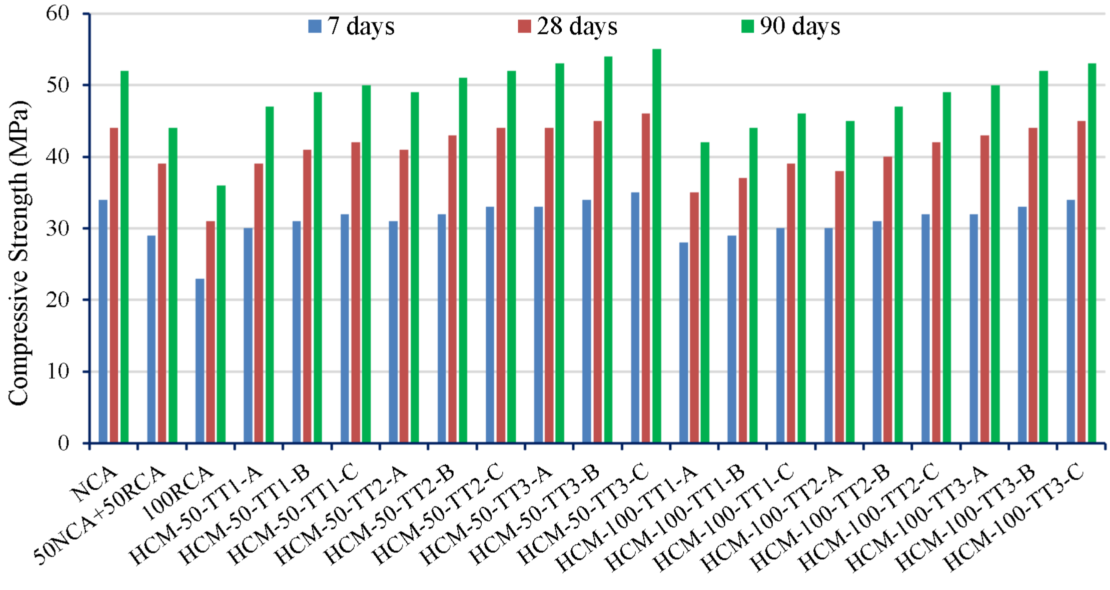


**Fig. 3** Effect of thermal treatment on compressive strength at different RCA contents with hybrid cementitious materials

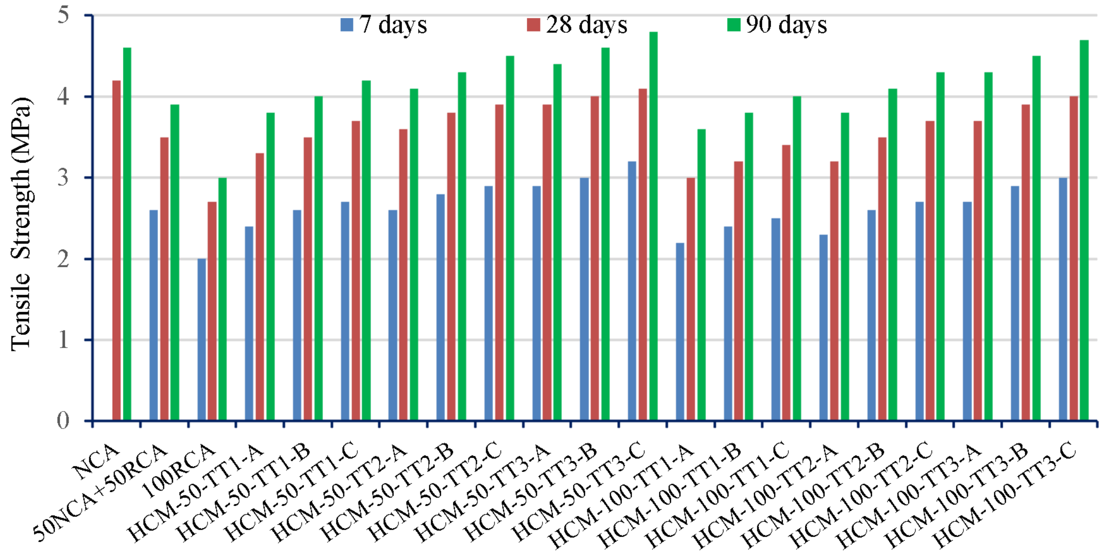


**Fig. 4** Effect of thermal treatment on tensile strength at different RCA contents with hybrid cementitious materials

at seven, twenty-eight, and ninety days, respectively. This indicates that bond development and matrix integrity were most favourable in the absence of RCA or SCMs. Among the RCA-containing mixes, those subjected to TT3 treatment consistently achieved the highest tensile strength values, confirming TT3's superior ability to restore strength compared to TT1 and TT2. In the HCM-50 series, TT1-treated mixes showed relatively lower early-age strength. For example, HCM-50-TT1-A recorded 2.4 MPa at 7 days, with moderate gains over time. On the other hand, TT2-treated mixes, such as HCM-50-TT2-C, demonstrated enhanced performance, reaching a maximum pressure of 4.5 MPa at 90 days. The TT3 group showed the best results in terms of tensile strength. Notably, HCM-50-TT3-B achieved approximately 96% of the control strength at 28 days, and HCM-50-TT3-C recorded 3.2 MPa (7 days), 4.1 MPa (28 days), and 4.8 MPa (90 days) – equal to or even surpassing the control at all ages. These improvements are attributed to enhanced IT and matrix densification resulting from the inclusion of 30% MK.

In the HCM-100 series (100% RCA mixes), the challenges associated with RCA's inferior quality were more evident. The lowest values were seen in mixes treated with TT1; for example, HCM-100-TT1-A only attained 2.2 MPa at 7 days and 3.6 MPa at 90 days. A minor improvement of 4.3 MPa was observed at 90 days in HCM-100-TT2-C, which was treated with TT2. Once again, the TT3-treated mixes performed best in this category. HCM-100-TT3-C recorded 3.0 MPa at 7 days, 4.0 MPa at 28 days, and 4.7 MPa at 90 days – slightly below the control but superior to other treated RCA mixes. Strength development was most significant for all combinations between 7 and 28 days, and continued gains for up to 90 days.

These results confirm that treatment quality is a critical factor in determining the tensile performance of RCA-based concrete. Particularly at greater RCA replacement levels, TT3 continuously performed better than TT1 and TT2. Furthermore, the combined use of MK and GGBS demonstrated a synergistic effect, enhancing tensile strength over extended curing periods through pozzolanic reactions and pore refinement.

### 3.4 Water absorption performance at 28 and 90 days

Water absorption serves as a key indicator of concrete quality and durability, providing insight into its internal pore structure and resistance to moisture ingress. In this study, concrete mixes incorporating 50% and 100% RCA, treated through three surface modification methods (TT1, TT2, and TT3), and supplemented OPC with MK and GGBS, were evaluated for water absorption at 28 and 90 days. These results were compared with a control mix composed solely of natural aggregates (see Fig. 5).

Water absorption generally increased slightly from 28 to 90 days, likely due to drying shrinkage and continued development of the pore structure. In the 50% RCA mixes (HCM-50 series), water absorption was generally higher than that of the control mix due to the inherently porous nature of RCA. Within the TT1 group, water absorption increased with MK content. For example, HCM-50-TT1-A recorded 3.8% at 90 days, while HCM-50-TT1-C, with 30% MK, reached 4.2%. TT2-treated mixes demonstrated moderate improvement; HCM-50-TT2-C had an

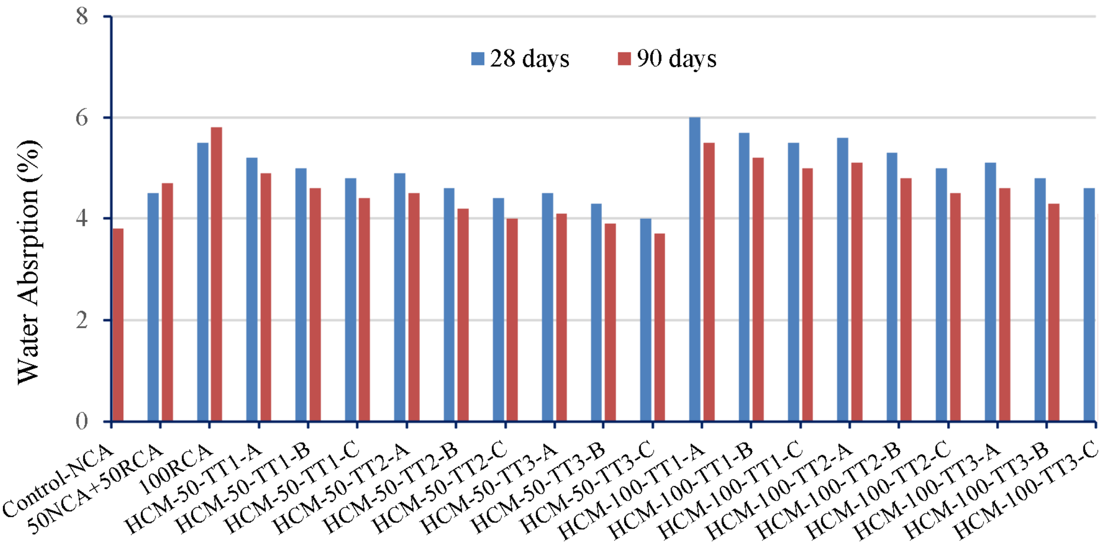


**Fig. 5** Effect of thermal treatment on water absorption at different RCA contents with hybrid cementitious materials

absorption of 3.9% at 28 days and 4.5% at 90 days. TT3-treated mixes showed the best performance, with HCM-50-TT3-C recording 4.1% at 28 days and 4.8% at 90 days, approaching the values of the control mix. These results suggest that TT3 was the most effective in enhancing RCA quality and limiting moisture penetration in partially recycled concrete. In the 100% RCA mixes (HCM-100 series), water absorption values were naturally higher but varied according to treatment method. TT1-treated samples showed minimal benefit; HCM-100-TT1-A and HCM-100-TT1-C reached 3.6% and 4.0%, respectively, at 90 days. TT2 treatment yielded slightly improved results, with HCM-100-TT2-C reaching 4.3% at 90 days. The best results again came from the TT3 group. HCM-100-TT3-C recorded 4.0% at 28 days and 4.7% at 90 days – the lowest among all 100% RCA mixes – demonstrating that TT3 significantly enhanced surface properties and reduced permeability even under complete RCA replacement.

The inclusion of MK and GGBS mitigated capillary connectivity by contributing to matrix densification, primarily when used in conjunction with high-quality RCA treatments. The combination of TT3 with MK and GGBS proved particularly effective in reducing absorption and enhancing durability. These findings align well with previous studies. It is widely acknowledged that RCA has higher porosity and water absorption than NCA, but this tendency can be significantly reduced through surface treatment and the addition of SCMs. For example, 50% RCA mixes treated with TT3 had water absorption values between 4.1% and 4.8% by 90 days, comparable to those of the control mix. This result is consistent with the findings of [42], which reported that thermal treatment combined with SCMs enhances the pore structure of RCA. Similarly, in 100% RCA mixes, TT3 reduced absorption to 4.7% at 90 days, in agreement with [37], which demonstrated that thermal methods and SCMs such as MK and GGBS lead to a denser microstructure and lower absorption.

Furthermore, the absorption values reported in this study are supported by [43], which showed that optimized treatment and inclusion of SCMs can mitigate porosity, even in concrete with complete RCA replacement. In contrast, TT1-treated 100% RCA mixes showed higher absorption values (up to 4.0%), consistent with the findings of [44], which reported that untreated or minimally treated RCA resulted in absorption values ranging from 5% to 8%, depending on the source and composition. In summary, the water absorption values observed in this work are realistic and confirm the benefits of TT3 treatment, particularly when combined with MK and GGBS. This enhances long-term durability by refining the pore structure and minimizing permeability, even in concrete made with high levels of recycled aggregate.

### 3.5 Environmental implications of thermal processing

It is widely considered that the thermal-mechanical treatment improves the quality of RCA. It also produces some by-products in the form of fines and partially hydrated cement paste. These fines are mostly smaller than 4.75 mm and are due to mortar detachment, which creates a problem in their disposal owing to their porosity and binding potential. If not recycled, they can also add to the landfill burden. Although several studies have been conducted on the re-carbonation or pozzolanic reuse of these fines, their value remains unavailable for unprocessed materials. In this study, the thermal treatment temperature was maintained below 300 °C, as temperatures above this point substantially increase energy demand; therefore, a performance-equalization approach was employed. However, a complete life cycle assessment (LCA), including emissions from heating, energy source quality, and fine fraction management, could be included in future work to determine whether the process is environmentally sound. Notably, this study provides insights into the behavior of concrete with high treated RCA and hybrid SCMs, but it does not consider specific control mixes, such as treated RCA with only OPC and NCA with SCMs. Thereby, the effects of RCA treatment from those of binder composition cannot be completely disentangled. A complete factorial experimental design is recommended for future research to uncover the individual and interactive effects of these parameters. As explicitly acknowledged, the current study does not include controls necessary to decouple the effects of RCA treatment from SCMs. Therefore, any observed performance improvements should be attributed to the integrated treatment rather than any individual intervention.

In addition to the thermal treatment of RCA, the overall energy footprint of the proposed approach must also consider the energy required for kaolin calcination to produce metakaolin and for the Los Angeles abrasion process. Furthermore, while metakaolin is highly reactive, high dosages (e.g., 30%) can be challenging to disperse due to its fine particle size and tendency to agglomerate, which may also increase material costs. These practical and environmental considerations underscore the need to optimise SCM content and treatment methods, striking a balance between performance gains and economic and ecological feasibility.

## 4 Limitations

While the study demonstrates the potential of integrating low-energy thermal treatment, mechanical abrasion, and hybrid SCMs to improve the performance of RCA-based concrete, it does not isolate the individual contributions of RCA treatment and SCM inclusion. The absence of dedicated control mixes (e.g., treated RCA with only OPC, or untreated RCA with SCMs) limits the ability to disentangle their respective effects. This integrated design was chosen to reflect an application-oriented approach, but it also represents a limitation in the experimental program. Future work should therefore focus on systematically investigating the isolated impacts of RCA treatment and SCMs, which would complement the present findings and provide a deeper understanding of their mechanisms. Another limitation of this study is that quantitative data on energy consumption or $CO_2$ footprint did not support the sustainability claims for low-temperature treatments. While the results indicate promising performance benefits, the absence of approximate life cycle assessment (LCA) data limits the ability to fully evaluate trade-offs between mechanical improvements and environmental impact.

## 5 Conclusions

This study introduced a novel integrated approach to enhance the performance of recycled concrete aggregates (RCA) in structural concrete by combining low-energy thermal treatments (TT1, TT2, and TT3) with mechanical abrasion and incorporating a hybrid system of supplementary cementitious materials (metakaolin and GGBS). This combination, particularly the stepped thermal treatment (TT3) and optimized SCM ratios, represents a unique contribution compared to previous studies that investigated these strategies separately. A series of experiments was conducted to evaluate the compressive strength, tensile strength, and durability of concrete mixtures containing varying proportions of treated RCA and SCMs, compared to conventional concrete mixes. The study demonstrated that the combination of mechanical abrasion and thermal conditioning is an effective strategy for enhancing the quality of RCA for use in structural concrete. Moreover, among the tested configurations, the concrete incorporating TT3-treated RCA and hybrid SCMs demonstrated the best overall performance. However, due to the integrated design, the effects of thermal treatment and binder composition are considered as combined. The following conclusions were drawn from the experimental findings:

- Effectiveness of RCA Treatment: Stepped thermal conditioning (TT3) enhanced the performance of both fresh and hardened concrete by significantly reducing the water absorption of RCA.
- SCMs' role: the addition of 20% GGBS and 30% MK enhanced long-term strength, pozzolanic reactivity, and microstructural densification.
- Optimized Composite Performance: When compared to untreated RCA mixes, concrete mixes containing TT3-treated RCA and optimized SCMs content demonstrated higher compressive and tensile strengths as well as reduced water absorption.
- Sustainability Potential: The proposed treatment and mix design reduce the demand for virgin aggregates

and OPC by integrating industrial by-products, thereby promoting eco-efficient and sustainable construction practices. Additionally, using alternative mineral admixtures in concrete, as well as recycling and repurposing construction and demolition wastes, can help reduce the quantity of cement and aggregates used.

In conclusion, this integrated approach – combining advanced RCA treatment with hybrid SCMs – provides a viable and sustainable pathway for producing durable, high-performance concrete that maintains structural integrity. These findings also support the broader adoption of RCA and SCMs in structural applications that align with the United Nations' Sustainable Development Goals (SDGs). By this method, it reduces all influences on virgin aggregates and Portland cement, thereby supporting sustainable construction. The thermal treatment process adds further energy demands. The net environmental gain will therefore depend on optimizing the treatment conditions in order to balance performance gains with energy efficiency.

Future work should encompass a detailed life cycle assessment (LCA) to quantify these trade-offs and inform the implementation of these applications in practical settings. Future work should also investigate additional binder–aggregate combinations that were not included in the present experimental matrix, as well as systematically isolate the individual effects of RCA treatment and SCMs. Furthermore, future studies should incorporate durability indices, such as chloride ion penetration and drying shrinkage, to provide a more comprehensive assessment of long-term performance. Moreover, microstructural analyses should be performed to directly evidence the pozzolanic reactions and matrix densification effects of MK and GGBS, thereby strengthening the mechanistic basis of the findings. Such studies will complement the integrated findings presented here and provide deeper mechanistic insight.

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