

Effects of Recycled Concrete Sand on the Physical, Mechanical Properties, and Hydration Heat of Mortar

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The use of Recycled Concrete Aggregates (RCA) is one of the solutions to the problems of both the high demand for natural aggregates by the construction industry, as well as the decrease in landfill demolition debris overload. However, the production of concretes or mortars based on RCA with qualities similar to those made with Natural Aggregates (NA) poses challenges. The main objective of this experimental study is to determine the influence of replacing 20%, 40% and 60% of Natural Sand (NS) with Recycled Concrete Sand (RCS) with the combination of replacing cement with different mineral additions: 10% Silica Fume (SF), 10% Limestone Powder (LP), 20% natural Pozzolana (PZ) and 20% Ground Blast Furnace Slag (GBFS) on the mechanical and physical properties of a plastic mortar. The results obtained revealed that RCS, rich in attached mortar, exhibits low physical properties such as low density, rough grain shape and high water absorption. Regarding the mechanical behavior of the obtained mortar, the results show that the presence of RCS has a positive impact on the Compressive Strength (S_c) accompanied by an increase of the hydration heat (Q) compared to the reference mortar. Moreover, the use of mineral additions improved the mechanical strength of the mortar, especially SF, which was the most active addition, followed by PZ. An empirical equation is proposed to predict the hydration heat as a function of the compressive strength, taking into account the cement type and the age of the mortar (≤ 10 days).

Keywords: Compressive strength, Hydration heat, Natural aggregates, Natural sand, Recycled concrete aggregates

Introduction

Concrete is the most widely used material in the construction industry, leading to high consumption of Natural Aggregate (NA) and the saturation of public landfills with demolition debris. The idea of recycling this waste into aggregates is not new, and its reuse in new concrete or mortar is a promising solution from both economic and ecological perspectives. This approach has enabled the construction industry to develop processes to recycle up to 100% of demolished concrete. However, producing high-quality concrete remains challenging due to the old cement paste attached to the Recycled Aggregates (RA). To obtain good outcomes, concrete is modified in various ways, including adjusting mix proportions, changing its composition, incorporating alternative waste materials, and adding admixtures.¹

Consequently, the combination of NA and RA (by substituting NA with RA) makes the cementitious

matrix of the new concrete more complex due to the heterogeneity introduced by the presence of old hardened cement paste.^{2,3}

According to most researchers, the use of RA leads to a decrease in workability, which requires either an increase in the Water-to-Cement ratio (W/C) or the use of an admixture to achieve a workability similar to that of NA concrete. It is important to note that workability depends on the water condition of the aggregate, its absorption rate, and the formulation method.⁴ Generally, Recycled Concrete Sand (RCS) has an absorption rate that can reach 13%, and it is sometimes estimated to be about 5 to 7 times higher than that of Natural Sand (NS).⁵

The study conducted by Haneol *et al.*⁴ which used two different types of aggregates with varying content of attached mortar, showed that RA1, with 28% attached mortar, caused a decrease in subsidence of approximately 23% and 45% for replacement rates of 25% and 50%, respectively, while RA2, with 12% attached mortar, decreased subsidence by 14% and 24%. Additionally, other researchers have pointed out

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an inversely proportional relationship between the rate of RCA incorporation and the slump of concrete and/or mortar.^{6,7} Minkwan *et al.*⁸ explained this by the rough surface of Recycled Concrete Aggregates (RCA) and its physical characteristics, such as high water absorption, which lower the workability of concrete. According to Rebeca Martínez-García *et al.*⁶ a decrease in the density of RCA-based mortar compared to NS-based mortar was noted, which aligns with expectations given the low density of RCA and the higher W/C ratio required.

In terms of mechanical properties, several studies have been done on the effect of coarse RA on resistance, but research on the incorporation of RCA in mortar has only just begun. Some researchers have mentioned that the use of RCA is limited due to its low characteristics, primarily its high absorption rate. Studies have shown that sand with an absorption rate of 6% to 13% generates a decrease in resistance of 4% to 36%.⁹⁻¹¹

Even if incorporating RCA in new concrete is feasible, researchers have recommended keeping the replacement rate below 30% because higher rates lead to a considerable drop in strength.^{12,13} This is supported by a study conducted by Rebeca Martínez-García *et al.*⁶ which found a decrease in compressive strength of 13.03%, 20.98%, and 33.99% for mortars containing 25%, 50%, and 100% fine RA respectively at 7 days, followed by reductions of about 19.55%, 25.68%, and 33.25% at 28 days compared to the control. At 90 days, the mixture with 25% RA showed an increase of about 1%, while the mixtures with 50% and 100% RA showed reductions of about 4.42% and 20.49% respectively.⁷

Regarding tensile strength, a decrease in values has been noted over time, approaching those of the control at 90 days; the mixtures with 50% and 100% RA showed decreases of around 1% and 7%, respectively, while the mortar with 25% RA showed an increase of 4%.⁶

In addition, the negative effect of RA as Recycled Pavement (RP) materials content is partially mitigated by the increase in strength and density as well as the good bond between NA and old RP.¹⁴ According to other researchers, a replacement greater than 30% and up to 100% might be feasible. Berredjem *et al.*⁵ observed an improvement in the strength of RCA-based mortars and explained this by the presence of anhydrous constituents in the old cement paste. Thus, the study by Kou *et al.*¹⁵ where they maintained

constant workability, showed an increase in the strength of mortar with an increase in the substitution rate: 25%, 50%, and 75% RCA, while 100% RCA had a strength similar to that of the reference concrete. Similarly, Gennis *et al.*¹⁶ concluded that small RA contributed to the improvement of strength by 10% to 15% as well as stiffness.

As mentioned earlier, attached mortar can negatively affect the properties of concrete. This has led researchers to explore processes for improving the quality of RCA-based concretes. Some have demonstrated that the application of the Volume of Mortar Equivalent method positively affects mechanical properties. According to Haneol *et al.*⁴ this formulation method has demonstrated an improvement in mechanical strengths, and he recommended its use with a mixture of 100% RCA for good results.

According to the study carried out by Minkwan *et al.*⁸ the use of mineral additions was highly beneficial, with most mixtures containing 50% RCA and additions in semi-normal dosages showing an increase in compressive strength of 4% to 17% and in tensile strength of 3% to 20%. However, a normal dosage of additions had a negative effect on the strength of the mixture at 100% RCA. Among the mineral additions, SF significantly increased the resistance of the control mixture due to its fineness and the presence of siliceous products.¹⁷ For mixtures with 50% RCA, the addition most contributing to the improvement of resistance was Ground Blast Furnace Slag (GBFS) at a normal dosage, followed by Fly Ash (FA), which resulted in a 34.6% increase in resistance.¹⁸

According to Paramond *et al.*¹⁹ the authors stated that a 20% incorporation rate of FA in concrete with RCA is optimal for improving mechanical strengths. On the other hand, Johny *et al.*²⁰ noted that adding 50% of S to concrete based on 50% RCA decreased its strength compared to that 0% of RCA at 28 days, but better strengths might develop in the long-term due to pozzolanic activity. Additionally, according to the study by Ragavi *et al.*¹⁸ using RCA (50% and 100%) with an absorption rate of 2.1%, they found that an effective dosage of SF contributing to strength development ranged between 7.5% and 10% for all replacement rates.

As a result, the majority of research work^{2,3,7,13} has focused on the valorization of coarse Recycled Aggregates (RA) in concrete, unlike the fine fraction, which results in large quantities during crushing and

is less studied due to its poor quality linked to the high content of attached mortar.

The novelty of this study lies in the simultaneous evaluation of the effect of replacing NS with RCS from demolished concrete and the incorporation of mineral additives on both the heat of hydration and the mechanical performance of mortars. Very few studies have addressed this dual substitution in a combined manner, despite its importance for optimizing the formulation of eco-friendly mortars that combine environmental sustainability with technical performance.

Taking into account the negative effects of RCS on physico-mechanical properties and hydration heat, this article presents the experimental and numerical results of our studies on the influence of the nature and dosage of mineral additions on the physical, mechanical properties, and hydration heat of eco-mortars with different substitution rates (20%, 40%, and 60%) of NS by RCS.

The replacement levels of 20%, 40%, and 60% for RCS were selected to evaluate the progressive impact of substitution on the fresh and hardened properties of mortar, while maintaining a balance between performance and sustainability. These intermediate levels allow for the identification of an optimal substitution threshold before potential negative effects, such as increased porosity, reduced strength, or altered hydration behavior become significant.

Several studies have adopted similar substitution rates for systematic evaluation. For instance, Pedro *et al.*²¹ investigated recycled fine aggregates in mortar with replacement levels ranging from 20% to 100%, and found that moderate levels (20–50%) provided a good compromise between mechanical performance and environmental benefit. De Brito and Saikia²² also recommend limiting the replacement rate to 60% to avoid excessive degradation in mechanical and durability properties.

Materials and Methods

Materials

The cement type selected for this research is Ordinary Portland Cement (OPC) CEMI 42.5, along with cement variants containing 10% of LP, 20% of NP, and 10% of SF and 20% of GBFS. The specific surface area of both the cement and additives was measured using the Blaine method. Physico-chemical and mineralogical characteristics of the materials used are summarized in Table 1. All mortars were prepared according to ASTM C (305-06)²³ standard specifications.

To prepare the mortar, two types of sand were used: natural river sand (NS) (0/4 mm) and RCS obtained from the crushing of old concrete blocks, manufactured in a laboratory as illustrated in Fig. 1 and 2. The RCS used was in an air-dry condition during mixing. The particle size curves of the two sands used is presented in Fig. 3. The proportions of mixtures for all mortars are detailed in Table 2.

In order to obtain the necessary workability for a plastic mortar, it is essential to use a superplasticizer, also called high water reducer. This water reducer is known to be the origin of Ether polycarboxylates, and greatly improves the rheological and mechanical attributes of cement paste.

Table 1 — Physico-chemical and mineralogical characteristics of materials used

Description	OC	LP	NP	GBFS	SF
Chemical composition (%)					
SiO ₂	20.58	0.55	46.4	42.20	92
Al ₂ O ₃	4.90	0.40	17.5	5.85	0.3
Fe ₂ O ₃	4.70	0.17	10.5	1.90	0.8
CaO	62.8	53.47	10.5	42.20	0.3
MgO	0.53	1.02	3.8	4.72	1.1
SO ₃	2.28	1.50	0.4	1.54	0.2
Residue	0.42	—	—	—	—
Free lime	2.17	—	—	—	—
Na ₂ O	—	0.02	3.4	0.12	0.7
K ₂ O	—	0.05	1.5	0.43	1.6
Loss of ignition	1.00	43.13	4.31	0.80	2.7
Finesses cm ² /g	2950	3200	3100	3150	—
Glass content, %	—	—	>15%	—	—
Mineralogical composition (%)					
C ₂ S	33.3				
C ₃ S	41.8				
C ₃ A	5.1				
C ₄ AF	10.7				

Table 2 — Characteristics of two type of sand used

Designation	NS	RCS
Fineness modulus	2.54	3.51
Sand equivalent (%)	81	92
Apparent density (kg/l)	1.51	1.23
Absolute density (kg/l)	2.74	2.51
Absorption coefficient (%)	1.85	7.23



Fig. 1 — View of the different sands used (NS/RCS)

Experimental Process

Specimens Preparation

To analyze the effect of RCS on the properties of mortars in both the fresh and hardened states, the mortars were prepared with cement-sand-water mass ratios of 1:3:0.55. Various doses of superplasticizer were

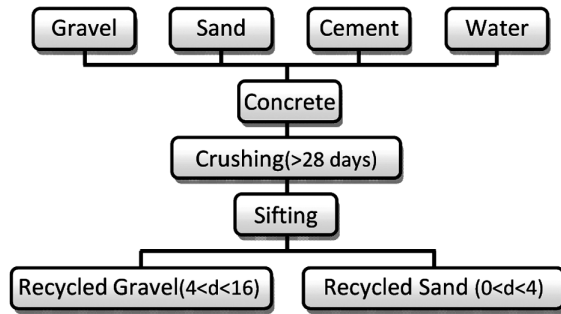


Fig. 2 — RCS Manufacturing Diagram

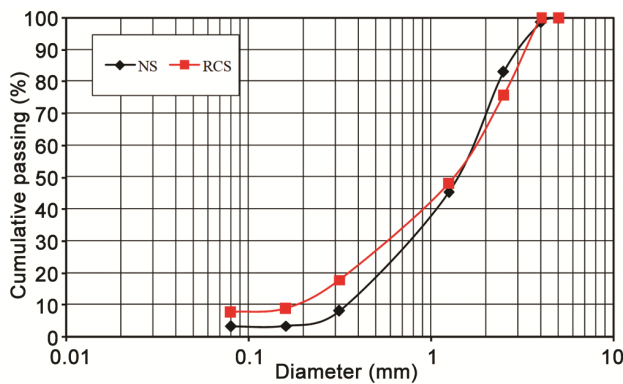


Fig. 3 — Particle size curves of the two sands used

added to ensure the mortars maintained a plastic consistency. The water content in the superplasticizer was subtracted from the total mixing water. A summary of the compositions for Sc and Q of each mortar is given in Table 3.

Workability

After mixing the various mortars, their fluidity was evaluated using the spreading method. This procedure was performed in accordance with ASTM C (230).²⁴

Setting Time

The socket test was carried out according to the specifications of the NF P (15-431)²⁵ standard using the Vicat device. The onset of hardening is defined as the time when a significant increase in the viscosity of the pulp is observed.

Compressive Strength

The compressive strength of all mortars was determined in accordance with the European standard EN (196-1).²⁶ Mortar specimens were prepared by casting 40 mm cubes. After 24 hours, the specimens were removed from the molds and immersed in water at 23°C. They were taken out of the water one hour prior to being subjected to compressive strength testing at 1, 3, 7, 28 and 90 days.

Hydration Heat

The Q test was carried out according to NF (15-436)²⁷ standard. The method is based on the Langavant Calorimeter. This method consists of

Table 3 — Mix proportion for all mortars studied for Compressive Strength (Sc) and Hydration Heat (Q)

Mixt	Cement (g)		NS (g)		RCS (g)		RCS %		SP (%)		Water (g) (%)	
	Sc	Q	Sc	Q	Sc	Q	Sc	Q	Sc	Q	Sc	Q
OC ₀	450	360	1350	1080	0	0	0	0	0.5	0.5	245.92	196.74
OC ₂₀	450	360	1080	864	270	216	20	20	0.7	0.7	245.29	196.23
OC ₄₀	450	360	810	648	540	432	40	40	1	1	244.35	195.48
OC ₆₀	450	360	540	432	810	648	60	60	1.1	1.1	244.03	195.22
LP ₀	450	360	1350	1080	0	0	0	0	0.5	0.5	245.92	196.74
LP ₂₀	450	360	1080	864	270	216	20	20	0.65	0.65	245.45	196.36
LP ₄₀	450	360	810	648	540	432	40	40	0.9	0.9	244.66	195.73
LP ₆₀	450	360	540	432	810	648	60	60	1.2	1.2	243.72	194.97
NP ₀	450	360	1350	1080	0	0	0	0	0.6	0.6	245.61	196.48
NP ₂₀	450	360	1080	864	270	216	20	20	0.8	0.8	244.98	195.98
NP ₄₀	450	360	810	648	540	432	40	40	1.1	1.1	244.03	195.22
NP ₆₀	450	360	540	432	810	648	60	60	1.3	1.3	243.40	194.72
GBFS ₀	450	360	1350	1080	0	0	0	0	0.5	0.5	245.92	196.74
GBFS ₂₀	450	360	1080	864	270	216	20	20	0.6	0.6	245.61	196.48
GBFS ₄₀	450	360	810	648	540	432	40	40	0.8	0.8	244.98	195.98
GBFS ₆₀	450	360	540	432	810	648	60	60	1	1	244.35	195.48
SF ₀	450	360	1350	1080	0	0	0	0	0.8	0.8	244.98	195.98
SF ₂₀	450	360	1080	864	270	216	20	20	0.9	0.9	244.66	195.73
SF ₄₀	450	360	810	648	540	432	40	40	1.05	1.05	244.19	195.35
SF ₆₀	450	360	540	432	810	648	60	60	1.1	1.1	244.03	195.22

quantifying the heat (Q) generated during the cement hydration, for five days, using a thermally insulated bottle, kept at a temperature of 23°C. The Eq. (1) calculates the Q of the mortar.

$$Q(t) = \frac{C}{M_C} \Delta\theta + \frac{1}{M_C} \int_0^t \alpha \Delta\theta dt \quad \dots (1)$$

where, C presented the thermal capacity (J/°C), m_c is the weight of cement (g), $\Delta\theta$ is the mortar heating difference to the ambient temperature (°C), and α is the total calorimeter thermal loss coefficient (J/h/°C).

Results and Discussion

Fresh State

Workability

Effect of RCS

To ensure consistent workability and filling capacity of the molds, the use of a superplasticizer was essential. It was observed that the required amount increases with higher percentages of RCS substitutes (Fig. 4). Berredjem *et al.*⁴ who found that the use of RCA negatively affects the slump compared to control mixtures, support this observation. This reduction is influenced by factors such as the absorption of the attached mortar, which reduces the mixing water, and the rough shape of the particles, which makes their mobility difficult.

Several researchers Huixia *et al.*¹⁰ and Zhao *et al.*²⁸ have noted that the incorporation of recycled aggregates generally decreases workability compared to reference mortar. This decrease can be attributed to the more angular shape of RA compared to NA, which hinders mortar workability. Similarly, the study by Rebeca Martinez-García *et al.*⁶ demonstrated that incorporating RCA into mortar

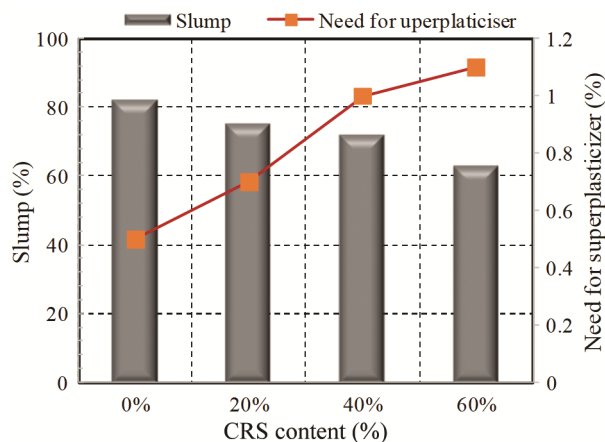


Fig. 4 — Need for superplasticizer for mortar without addition

increases the water-to-cement ratio (W/C ratio). The authors attributed this increase to the heterogeneity of RCA, their porosity and the presence of reactive products on their rough surfaces, which require more water for wetting.

Effect of the Combination of RCS and Mineral Additions

Based on the data presented in Fig. 5, it is evident that certain mineral additions contributed to reducing the amount of the superplasticizer required. For example according to the Fig. 5a, with an addition of 10% LP, the mortar required only 0.5%, 0.65%, 0.9%, and 1.2% superplasticizer for mixtures containing 0%, 20%, 40%, and 60% RCS, respectively. This requirement decreased to 0.5%, 0.6%, 0.8%, and 1% when 20% of the cement was replaced with GBFS (Fig. 5c). Even results for authors mineral additives such as SF and PZ (Fig. 5b and 5d).

This improvement in the rheological behavior of mortars as the percentage of fines increases can be explained by the reduction in void volume due to the presence of fine particles from the mineral additions. The slower reactivity of these particles with water allows for the retention of water within the voids in the mortar after mixing, thereby increasing the compactness of the mixture. All these factors contribute to the improved workability. Pramod *et al.*¹⁹ observed that incorporating GBFS into RCA-based concrete reduced slump by approximately 2.01% due to the particle shape of GBFS and its larger surface area, requiring more water for wetting and thus reducing slump.

Setting Time

Effect of RCS

The initial and final setting times of mortar as a function of the replacement rate of NS by RCS. It is clearly depicted that the setting time decreases inversely with the substitution rate of NS by RCS. Specifically, the results in Fig. 6 demonstrate that incorporating 60% RCS leads to a significant reduction of 59.55% and 31.67% in the initial and final setting times, respectively, compared to mortar made with 100% NA. This reduction is primarily attributed to the presence of anhydrous cement grains from the old mortar attached to RCS grains. Upon contact with water, these grains react quickly to form new calcium silicate hydrate (CSH) networks, accelerating the solidification (setting) of the cementitious paste. Consequently, the setting period of mortars containing RCS is shortened by

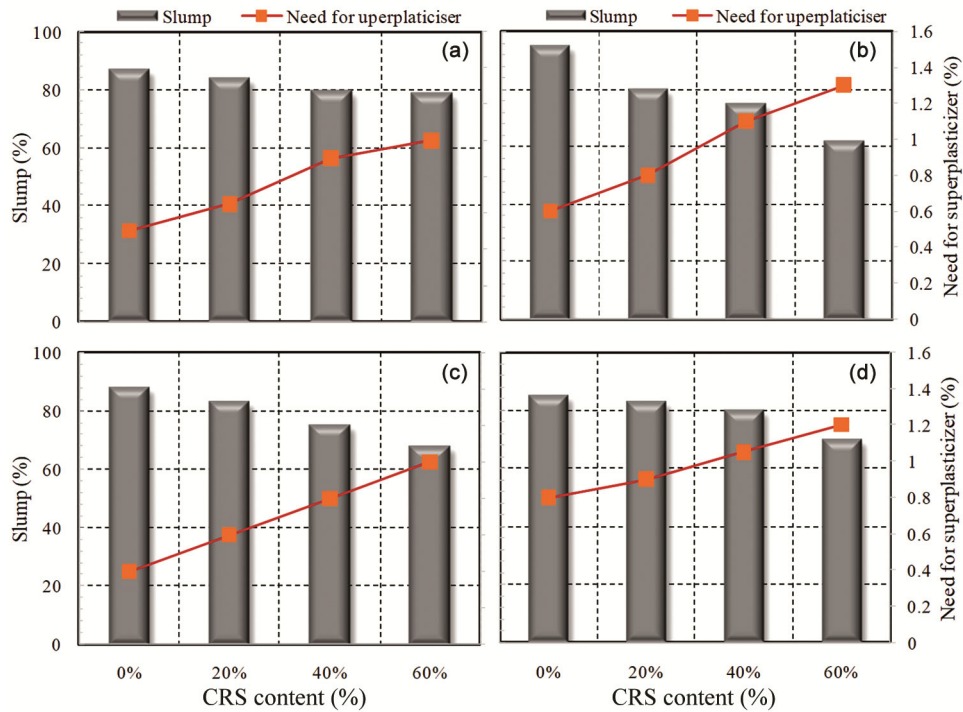


Fig. 5 — Need for superplasticizer for mortar containing several type of addition: (a) LP, (b) PZ, (c) GBFS, (d) S

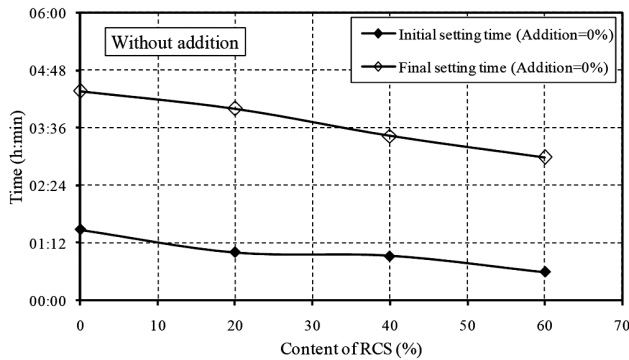


Fig. 6 — Effect of RCS in initial and final setting time for cement without mineral additives

approximately 13.3% and 17.34% for substitution rates of 40% and 60% RCS, respectively.

Meziane *et al.*²⁹ conducted a study indicating that replacing NS with crushed sand (CS) significantly influences setting times, resulting in reductions of 74 and 105 minutes compared to control mortar for different types of cement. This variation in setting times among the different mortars is attributed to their respective compositions. Furthermore, Katz and Kulisch³⁰ investigated mortar performance incorporating RCA and observed systematic increases in both initial and final setting times for these mixtures. The extent of this increase correlates with

the quality of the recycled aggregates used, suggesting a notable impact of RCA composition. Moreover, the influence on final setting time varies with the water-to-cement ratio: a lesser effect is noted for mixtures with a low water-to-cement ratio, while a more pronounced effect is observed for those with a high ratio.

Effect of the Combination of RCS and Mineral Additions

The LP does not significantly affect the initial setting time, except for rates of 20% and 60% RCS, where delays of 11 minutes and acceleration were observed for the 60% RCS rate compared to others. However, LP exerts a notable influence on the final setting time, which becomes increasingly significant with higher substitution rates of NS by RCS, leading to differences of up to 57 minutes for the mixture containing 60% RCS. This observation highlights LP's role in accelerating the setting time process (Fig.7a).

When substituting cement with 20% of PZ, there appears to be minimal impact on the initial and final setting times of mortars containing RCS (20%, 40%, and 60%). In contrast, when incorporated into the control mixture with 100% NS and PZ accelerates the initial setting time by approximately 24 minutes while delaying the final setting time by 28 minutes

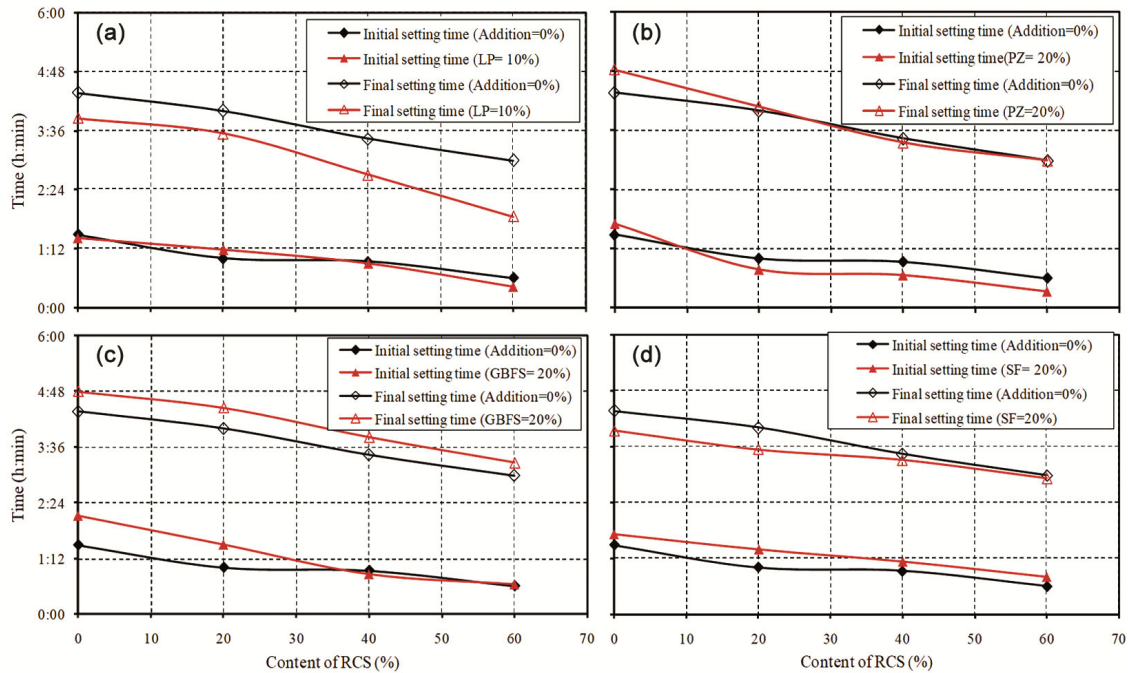


Fig. 7 — Effect of RCS in initial and final setting time for cement with mineral additives: (a) LP, (b) PZ, (c) GBFS, (d) SF

(Fig. 7b). This phenomenon is likely due to the high water absorption capacity of PZ grains, which reduces the water available in the cement paste, thereby decreasing the Q necessary for hardening. These observations align with findings from Laoufi *et al.*²³ who reported that PZ increases the water demand of concrete, influencing Q kinetics and prolonging setting time.

From the results presented in Fig. 7c, it is evident that incorporating 20% GBFS delays the setting time by approximately 38 minutes for mortar containing NS. This delay is attributed to the latent hydraulic properties of S, which slows down chemical reactions and Q kinetics by impeding the formation of calcium silicate hydrate (C-S-H) crystals crucial for hardening. However, this time difference diminishes as the RCS content in the mixture increases, considering RCS acts as a setting accelerator. Notably, the effect of GBFS becomes neutral from 40% RCS onwards.

When incorporating 10% of SF increases the initial setting time, with the maximum delay observed at 20% RCS, amounting to 23 minutes, while NS and 40%, 60% RCS show delays of 14 and 12 minutes respectively as follows in Fig. 7d. Conversely, an acceleration in the final setting time by 28 minutes was noted for the mixture with 20% SF, which decreases proportionally with increasing RCS content, down to 4 minutes for 60% RCS. These results are

consistent with previous studies Zhao *et al.*³² and Sirajuddin *et al.*³³ indicating that mineral additions impact setting time by altering the Q product volume through reduced mixing water, thereby prolonging the initial setting time.

Hardend State

Compressive Strength

Effect of RCS

The evolution of mechanical strength in various mortars at 1, 3, 7, 28, and 90 days, with varying substitution rates of RCS is showed in Fig. 8a. These results clearly demonstrate the dependence of strength evolution on the amount of RCS. Importantly, the presence of RCS positively affects strength, surpassing that of ordinary sand-based mortar from the third day onwards.

Analysis of the 28-day results reveals strength improvements compared to mortars formulated solely with NS: increases in compressive strength of 8.5%, 17.4% and 15.4% respectively, and gains of approximately 3%, 9%, and 12% in strength for RCS substitution rates of 20%, 40%, and 60%. This strength enhancement is likely due to the high quality of the parent concrete, which remained uncontaminated and unexposed to adverse conditions, as well as the coarse granularity of RCS, typically used for producing robust mortar or concrete.

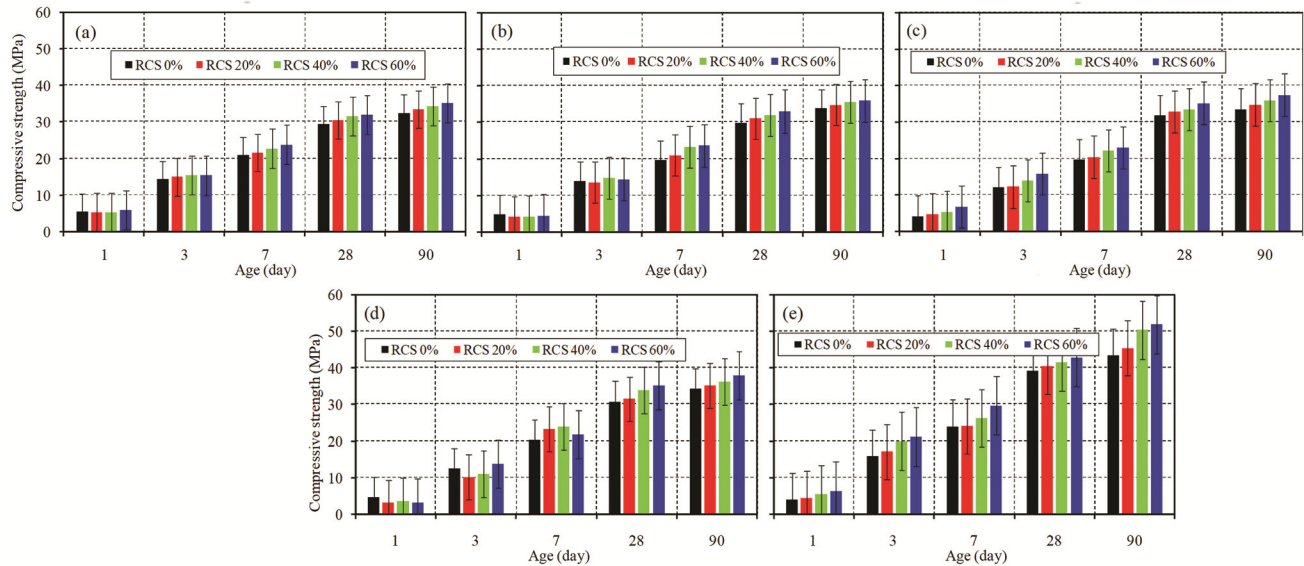


Fig. 8 — Effect of RCS in compressive strength for cement with mineral additives: (a) without minerals, (b) LP, (c) PZ, (d) GBFS, (e) SF

Moreover, the use of an admixture has reduced the required water quantity to achieve equivalent workability. This reduction in water content is crucial for obtaining a durable mixture. The irregular shape of RCS also likely enhances the bond between the paste and aggregate.

Berredjem *et al.*⁵, Martínez *et al.*⁶ and McGinnis *et al.*¹⁶ have consistently shown that incorporating RS in mortars does not compromise mechanical performance; instead, it enhances compressive strengths, especially when RCS completely replaces NS.

Furthermore, according to Haneol *et al.*⁴ the mechanical performance of concretes containing RCA primarily depends on aggregate quality rather than mortar content. Lower mortar content tends to yield mechanical performance comparable to control samples at early stages, with superior performance developing over time, surpassing control strengths at 56 days.

The observed strength gain in mortars incorporating the RCS can be attributed to several microstructural improvements. One significant factor is the densification of the interfacial transition zone (ITZ). RCS particles often contain residual adhered cement paste, which can enhance chemical bonding at the interface with the new cement matrix, resulting in a denser and stronger ITZ compared to mortars with natural sand according Pedro *et al.*²¹ and Zhang *et al.*³⁴ founded that the reduction in the mechanical properties of RCA is attributed to the

presence of old mortar, which negatively affects the performance of the RCA. The composition of RCA also includes a higher proportion of ITZ compared to NA.

Effect of the Combination of RCS and Mineral Additions

When combining mineral additions with RCS in mortar, it has been observed that the Sc are proportional to the rates of RCS substitution, despite the negative effect at young age of LP and GBFS presented by a decrease in Sc in the first days, mainly due to the dilution effect (Fig. 8b). These observed low mechanical properties may be due to its slow GBFS reactivity at an early stage. From the third day, we can see the beneficial effect of this combination where SF seems to be the most active addition with an increase of about 15.15% followed by PZ with 14.3% in Sc at 90 days for mortar with 60% RCS as indicated in Fig. 8c and 8e. This difference in value of Sc is due to the large specific surface area of this addition, which makes the matrix denser and more rigid. This result is confirmed by Ju *et al.*⁸ and Ragavi *et al.*¹⁸ that showed that the use of mineral additives significantly improved the Sc of RCA. The use of SF resulted in an increase in Sc of up to 97% compared to the reference specimen. Recent studies Ju *et al.*⁸, Pramod *et al.*¹⁹ and Johny *et al.*²⁰ have highlighted the positive impact of the addition of GBFS on the properties of concrete. The integration of 20 to 30% of GBFS led to a significant increase in Sc from the seventh day. However, it is important to note that

higher proportions of GBFS may initially decrease S_c , although long-term benefits are anticipated due to the pozzolanic activity of the material (Fig. 8d).

In another order, it can be clearly seen that the substitution of cement by silica fume generates a significant increase in S_c while increasing the RCS rate, this influence is mainly due to the filling effect and also to its long-term pozzolanic activity. It is clearly noted that PZ is one of the additions that play an important role in the improvement of mechanical resistance, especially in the long term, with an increase of about 7%, 13% and 14% for mixtures 20%, 40% and 60% respectively at 90 days. This improvement is the result of the reaction between PZ and lime, from the Q of cement, which leads to the formation of the second generation of C-S-H. These results are in line with other research^{8,18}, which has shown that the integration of mineral additions can improve the mechanical properties of the mortar in the long term, especially when using silica fume as an addition.

Hydration Heat

Effect of RCS

The evolution of heat hydration and heat flux of mortars containing different levels of RCS are presented in Fig.9a and 9b. It is evident that RCS

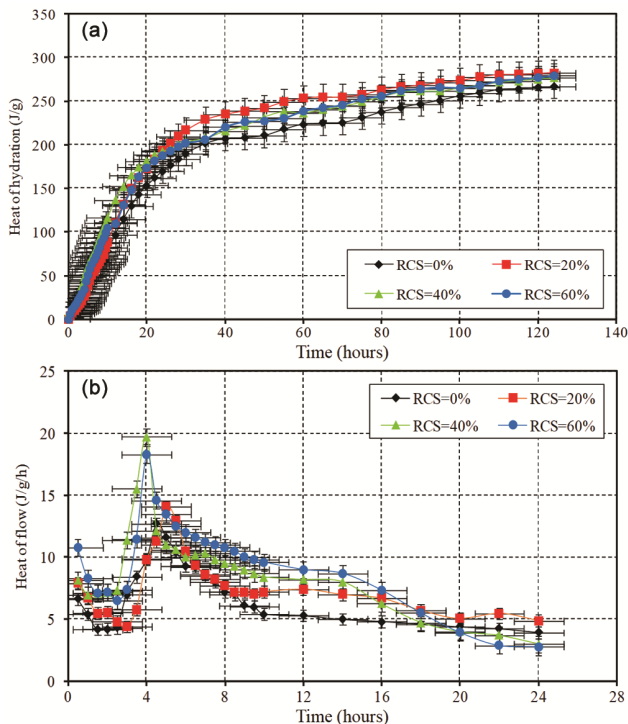


Fig. 9 — Evolution of heat of hydration (a) and heat of flow (b) for mortars with RCS

increases the mixture temperature and accelerates the appearance of the peak, thereby enhancing the heat of Q compared to the control mortar. This indicates additional Q caused by the anhydrous cement present in RCS. Amine *et al.*³⁵ examined the cementing properties of fines from RCA and observed higher heat levels during initial wetting phases in RCA compared to pure cement at equivalent temperatures. These elevated heat flux levels confirm the presence of reactive aluminous compounds in RCS. In contrast, normal fine sand exhibited the lowest heat flux, suggesting a lack of reactive substances contributing to cementitious properties when mixed with water. Additionally, Brice Delsaute and Staquet³⁶ studied the impact of RCA on volume change, noting increased temperatures in mixtures where NA was substituted with RCA, especially at higher substitution rates (30% sand and 30-100% RCA). They attributed this to the nature and porosity of the aggregates. Also El-Hadj Meziane *et al.*³⁷ compared mortars based on CS and NS, finding that mortars exhibited rapid Q kinetics, particularly noticeable in early stages where the peak heat release occurred approximately 2.5 hours earlier compared to NS based mortar. Moreover, Eduard *et al.*³⁸ investigated the influence of RCA moisture and water-to-cement ratio (W/C ratio, 0.45 and 0.6) on Q processes. They found that maximum temperatures were reached by dry RCA for both W/C ratios, with the ratio affecting Q duration. The similar studies by Marija Nedeljković *et al.*³⁹ and Marija Nedeljković *et al.*⁴⁰ indicated that cement paste and various mortars show similar Q tendencies. However, incorporating fine RCA resulted in slight variations depending on moisture and sand origin used in the mortar.

Additionally, Silva *et al.*⁴¹ confirmed that the rougher surface texture and higher porosity of RCS contribute to improved mechanical interlocking and water retention. This retained water can act as internal curing, promoting continued hydration and leading to the refinement of the pore structure, which enhances strength and durability.

Effect of the Combination of RCS and Mineral Additions

The Q of cement is primarily influenced by its composition, including mineral additives, and their impact on the Q process. From the results obtained, it is observed that at the 12-hour mark, the highest heat release was recorded for the mixture containing 10% of SF at 168.66 J/g, followed by the cement-only mixture at 136.27 J/g. The mixtures with 10% of

limestone, 20% of PZ, and 20% GBFS showed heats of 177.07 J/g, 153.84 J/g and 146.78 J/g respectively. Comparing the effects of the remaining three additives, it is evident that the presence of mineral additives such as LP and PZ significantly alters the Q process. These additives tend to decrease the heat release compared to the mixture containing RCA and the control mixture. The LP cement exhibits rapid Q kinetics, reaching 70% of total Q within the first day and peaking at around 90% by the third day. Initially, its heat release closely matches that of cement-only mixtures, countering the dilution effect caused by reduced clinker content due to its physical properties. In contrast, PZ shows slower reactivity due to its pozzolanic nature, gradually activating over time. Briki *et al.*⁴² and Boubekour *et al.*⁴³ highlights the benefits of adding LP fines to cement, particularly in accelerating early hydration stages. It has been demonstrated that LP accelerates initial hydration kinetics, promoting rapid formation of C-S-H gels and reducing setting time.

On the other hand, the PZ addition decreases the heat of hydration of the mixture by reacting slowly with $\text{Ca}(\text{OH})_2$ in Portland cement, forming hydrated products that reduce the availability of $\text{Ca}(\text{OH})_2$ for heat generation. Additionally, PZ acts as a filler in the cement paste, reducing the availability of cement particles for hydration, thereby slowing down the process. Previous studies Boubekour *et al.*⁴³ have confirmed that using PZ as a cement substitute significantly reduces heat production during hydration, thereby decreasing the risk of thermal cracks in concrete. Generally, the heat released by pozzolanic materials is estimated to be about half of that produced by Portland cement (Fig 10a and 10b). These results are consistent with those reported by Boubekour *et al.*⁴⁴ where they found that natural pozzolana has a small effect.

In contrast, GBFS addition has a notable effect on reducing hydration heat due to its slow reactivity and high content relative to cement. Higher incorporation rates of GBFS further decrease heat release due to its dilution effect on the reactive hydrates of cement. This finding is consistent with conclusions drawn in Ahmad *et al.*⁴⁵ which demonstrate that partial replacement of cement with GBFS modifies hydration properties, reduces early-age heat release and shrinkage, and yet enhances longterm durability through its hydraulic reactivity. A potential problem with concrete is its

strength and durability, which is governed by several factors such as lower values of compressive strength, high chance of clogging, and less resistance to corrosion in severe environments.⁴⁶

Ten-Day Prediction of the Hydration Heat Depending on the Compressive Strength

Little investigation found that there exists a relationship between the compressive strength and heat of Q of cements. After many adjustments and several verifications of the experimental results found in this research, an exponential shape relation has been founded to predict the heat of Q depending on the compressive strength of mortars containing recycled concrete sand, the type of addition, and the age of mortar. The error deviation Eq. (2) is calculated for all points as the difference between the calculated Q heat and those measured.

$$\text{Error} = \sqrt{\frac{(Q_{\text{Predicted}} - Q_{\text{measured}})^2}{n}} \quad \dots (2)$$

The relationships between the compressive strength and the heat of Q proposed in this study can be written as follows:

$$Q(t) = ae^{0.03S_c} + bt \quad (\leq 10 \text{ days}) \quad \dots (3)$$

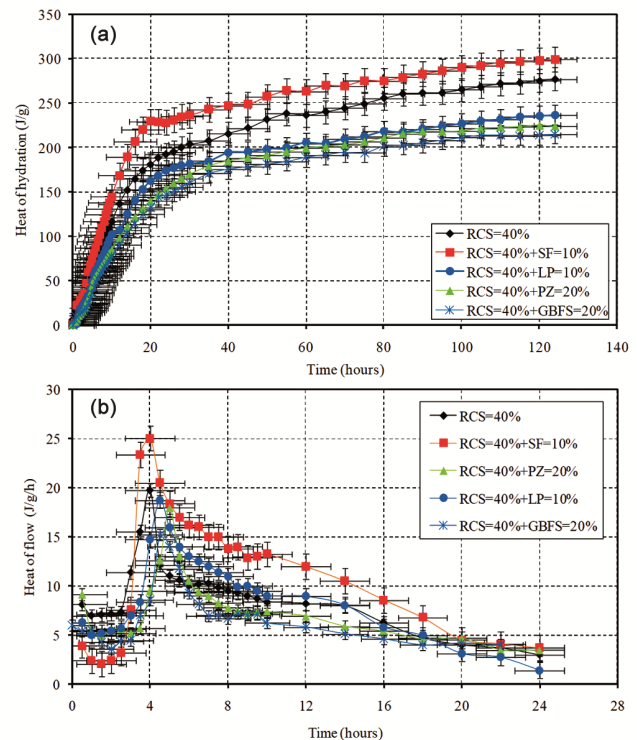


Fig. 10 — Evolution of heat of hydration (a) and heat of flow (b) for mortars with RCS and different type of mineral additives

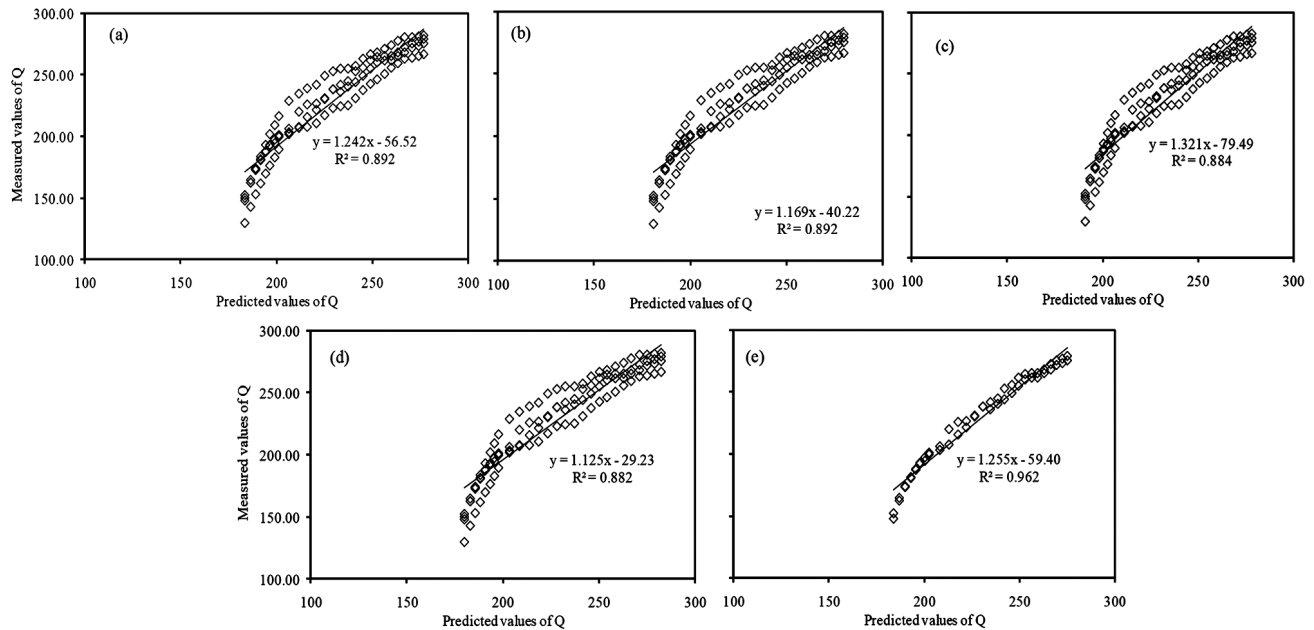


Fig. 11 — Comparison between measured and predicted Q values for mortar with RCS and mineral addition: (a) without minerals, (b) LP, (c) PZ, (d) GBFS, (e) SF

Table 4 — Values of parameters of the Eq. (3) for different cement types

Cement type	Values of a	Values of b	Equation of correlation	Coefficient of correlation R^2
OC ₄₀	157.4	0.52	$y = 1.242x - 56.52$	$R^2 = 0.892$
LP ₄₀	159.5	0.55	$y = 1.169x - 40.22$	$R^2 = 0.892$
NP ₄₀	159.7	0.57	$y = 1.321x - 79.49$	$R^2 = 0.884$
GBFS ₄₀	159.6	0.68	$y = 1.125x - 29.23$	$R^2 = 0.882$
SF ₆₀	158	0.42	$y = 1.255x - 59.40$	$R^2 = 0.962$

where, Sc (MPa) is the compressive strength of mortar, $Q(t)$ is the hydration heat with the time, a and b are parameters depending on the type of cement used which is determined by the minimization of error deviation value and t (days) is the age of mortar which must not exceed 10 days. The values of the parameters of the Eq. (3) are presented in Table 4.

The comparison between the measured and predicted values using the Eq. (4) is presented in Fig. 11 for several mixtures studied, in which a perfect alignment with a satisfactory correlation coefficient is obtained.

Verification and Validation of the Equation Proposed

To validate the Eq. (3) five experimental results published in the literature^{29,41,47-49} were chosen. The Table 5 compares the heat of Q results from these findings with the calculated values from Eq. 3. According to the Table 5, it is clear that the results demonstrate a satisfactory correlation coefficient its closer to unity.

Table 5 — Comparison of heat of hydration measured and calculated by Eq. (3) for five sets of data

Formulation of mortar	Equation of correlation	R^2
Crushed sand, LP, PZ ²⁹	$y = 1.223x - 47.96$	0.91
NS, LP, PZ, GBFS ⁴¹	$y = 1.218x - 50.28$	0.95
NS, OPC ⁴⁷	$y = 1.243x - 54.31$	0.95
NS, LP ⁴⁸	$y = 1.261x - 57.38$	0.92
NS, LP+PZ ⁴⁹	$y = 1.255x - 59.40$	0.96

Conclusions

The study conducted on the incorporation of RCS in mortar mixtures has revealed several key insights regarding its performance and potential for valorization. The results confirm that RCS derived from old constructions can partially substitute natural sand in mortar formulations without significantly affecting their physical and mechanical properties. This conclusion is supported by the experimental findings of the present research, which demonstrate that mortars incorporating RCS exhibit physical and mechanical properties comparable to those of conventional mortars. Future perspectives of this study include a

deeper investigation into the treatment parameters of recycled sand, as well as an analysis of its long-term behavior, particularly in terms of durability under aggressive environmental conditions. Furthermore, additional research focused on optimizing mortar and concrete formulations using RCS will help expand the application range of this material. These findings also pave the way for practical uses, especially in non-structural construction works, the prefabrication of secondary elements, and environmentally driven projects, where the reuse of construction waste represents both a major challenge and a significant opportunity in civil engineering.

Conflict of Interest

The authors declare that they have no conflict of interest.

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