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Orginal Article

Behaviour of eco-friendly mortar containing recycled concrete sand in fresh and hardened states

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Abstract: 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 and the reduction of landfill demolition debris overload. However, the production of concrete or mortar 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) on the mechanical and physical properties of eco-friendly mortar. The results obtained revealed that RCS, rich in attached mortar, exhibits low physical properties such as low density, rough grain shape, and highwater absorption. Regarding the mechanical behaviour of the mortar produced, the results show that the presence of RCS has a positive impact on the compressive strength (Sc). However, it has a negative effect on shrinkage.

Keywords: Eco-friendly, recycled concrete sand, natural sand, strength, weight loss

1. Introduction

The recycling of construction and demolition waste as aggregates in concrete is common and standardised in many countries. It offers a sustainable and cost-effective solution to address the environmental challenges faced by the construction sector. In particular, it supports efforts to reduce the carbon footprint of the cement industry, which aims for a target of less than 0.8 Gt/year by 2050 [1,2]. The use of recycled aggregates from waste not only helps conserve natural resources and reduce reliance on landfills, but also promotes the development of a more sustainable built environment. However, the fine fraction of this waste is rarely utilised. Even when permitted, guidelines are often very conservative and generally do not apply to structural concrete. Due to its poor quality, linked to the high content of attached mortar, combining both types of aggregates (natural and recycled) complicates the cementitious matrix of the new concrete. This complexity arises from the heterogeneity introduced by the presence of old hardened cement paste.

The characteristics of recycled concrete have been extensively studied by researchers worldwide [3-7]. Unlike natural aggregates, recycled aggregates are more porous, have a higher water absorption coefficient, contain hydrated compounds, and exhibit interfacial transition zones. Jian Liu et al. identified three main interfacial transition zones (ITZs) in recycled concrete (RC): the interface between the old aggregate and the new paste (ITZ1), the interface between the old aggregate and the old paste (ITZ2), and the interface between the new paste and the old paste (ITZ3) [8]. These are often considered mechanical weak points in concrete. Therefore, it is crucial to anticipate the behaviour of recycled aggregate concrete before its use in construction.

Most research studies [4,6,9,10] have observed that replacing natural aggregates with recycled ones leads to a decrease in slump, necessitating either an increase in the water-to-cement (W/C) ratio or the use of admixtures to achieve workability similar to that of natural aggregate concrete (NAC). This is due to the presence of adhered mortar on the surface of recycled aggregates, which contains microcracks [11].

It is important to note that this decrease is more pronounced when using the fine fraction. For this reason, Jang et al. [4] reported a slump reduction of about 23% to 45% for substitution rates of 25% and 50%. This is mainly due to the high porosity of fine recycled aggregates.

Regarding strength, numerous studies have been conducted on the effect of coarse recycled aggregates (RA) on mechanical performance. However, research on the incorporation of RCS in mortar is still in its early stages. Some researchers have indicated that the use of RCS is limited due to its weak characteristics, particularly its highwater absorption. A study conducted by Harich et al. [12], focusing on the performance of concrete incorporating recycled coarse aggregates (RCA) as a partial replacement for natural coarse aggregates (NCA) with substitution rates ranging from 0% to 100%, showed a gradual decrease in mechanical strength as the proportion of RCA increased.

Several studies [13-16] have shown that sand with an absorption rate of 6% to 13% leads to a reduction in strength ranging from 4% to 36%. Conversely, another high-quality RCS with an absorption rate of 5.4% caused a strength reduction of approximately 26% to 30% [17].

Although incorporating RCS into new concrete is possible, differences in replacement rates have been observed. Some researchers recommend not exceeding a 30% incorporation rate, as beyond this threshold, a significant decrease in strength has been noted [9,18,19].

According to Kępniak and Łukowski [20], the optimal replacement level of natural sand with recycled sand in mortar ranges between 40% and 60%. This proportion ensures good flexural and compressive strength while also reducing costs and environmental impact.

Other researchers [21,22,24] have found that an incorporation rate above 30%, up to 100%, could be feasible. They observed an improvement in the strength of RCS-based mortars and explained this by the presence of unhydrated components in the old cement paste, as well as the contribution of small-sized RA to enhancing strength and stiffness.

Similarly, the study by Kou et al. [23], in which they maintained constant workability, showed an increase in strength with substitution rates of 25%, 50%, and 75%, while 100% RA exhibited strength similar to that of the reference concrete.

Likewise, McGennis et al. [24] concluded that small-sized RA contributed to a 10% to 15% improvement in both strength and stiffness.

Berredjem Layachi et al. [25] observed that replacing natural sand with recycled sand positively affected the mechanical performance of mortar. They attributed this strength increase to the presence of anhydrous particles that had not yet undergone hydration.

Residual mortar can degrade concrete properties, prompting researchers [9,26,27] to explore methods for improving the quality of concrete containing recycled aggregates (RA). Some studies have shown that the Equivalent Mortar Volume (EMV) method can enhance mechanical properties. According to Jang et al. [4], this mix design method has proven effective in increasing mechanical strength, and it is recommended for use with a 100% recycled aggregate mix to achieve good results.

From another perspective, Xie J et al. [28] suggested adding mineral admixtures to mitigate the negative effects of recycled aggregates (RA). For example, substances such as slag, silica fume, and fly ash have demonstrated superior performance when used in concrete made with natural aggregates (NA).

Moreover, Mohammad Nadeem Akhtar et al. [29] demonstrated in their study that replacing 12.5% of cement with silica fume improved the strength of concrete made with different types of sand.

A comparative study by Berredjem et al. [30] between natural and recycled aggregates showed that the capillary absorption of concrete containing RA is higher than that of reference concrete. This is attributed to the quality of recycled sand, which contains porous cement paste and a large amount of fine particles.

The incorporation of recycled sand significantly affects the shrinkage of concrete and mortar, as they are often more porous and absorbent. This leads to significant shrinkage, which primarily depends on the quantity and quality of the RA, as well as the amount of fines present in the sand.

Guo et al. [31] noted that a substitution rate of 50% to 100% resulted in an increase in shrinkage of approximately 2.94% to 12.13% compared to control concrete. This finding aligns with those of other researchers [32-34].

In addition, the potential negative effects associated with the use of recycled aggregates (RA), specifically recycled pavement materials (RP), are partially offset by several compensating factors. These include the observed increase in compressive strength and overall density of the mixture, as well as the strong interfacial bond that forms between the natural aggregates (NA) and the aged recycled pavement particles [35].

The main objective of this experimental study is to determine the influence of replacing 20%, 40%, and 60% of NS with RCS on the fresh and hardened states of mortar containing ordinary Portland cement. This approach also contributes to the conservation of natural resources by substituting conventional building materials with materials recovered from construction waste.

2. Materials and experimental methods

2.1. Materials used

The cement type chosen for this research is ordinary Portland cement CEM I 42.5 (OPC), along with cement variants containing 10% LP, 20% NP, 10% SF, and 20% GBFS.

The specific surface area of both the cement and additives was measured using the Blaine method. The physico-chemical and mineralogical characteristics of the materials used are summarised in Table 1. All mortars were prepared according to ASTM C305-06 standard specifications. The proportions of mixtures for all mortars are detailed in Table 2.

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 Fig. 2, respectively. The particle size curves of the two sands used are presented in Fig. 3. In order to obtain the necessary workability for a plastic mortar, it is essential to use a superplasticiser, also called a high-range water reducer. This water reducer is based on polycarboxylate ethers and greatly improves the rheological and mechanical attributes of cement paste.

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

Description	OPC
SiO_2	20.58
Al_2O_3	4.90
Fe_2O_3	4.70
CaO	62.8
MgO	0.53
SO_3	2.28
Residue	0.42
Free lime	2.17
Na_2O	/
K_2O	/
Loss of ignition	1.00
Finesses cm^2/g	2950
Glass content, %	/
C_2S	33.3
C_3S	41.8
C_3A	5.1
C_4AF	10.7

Table 2. Characteristics of two types 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

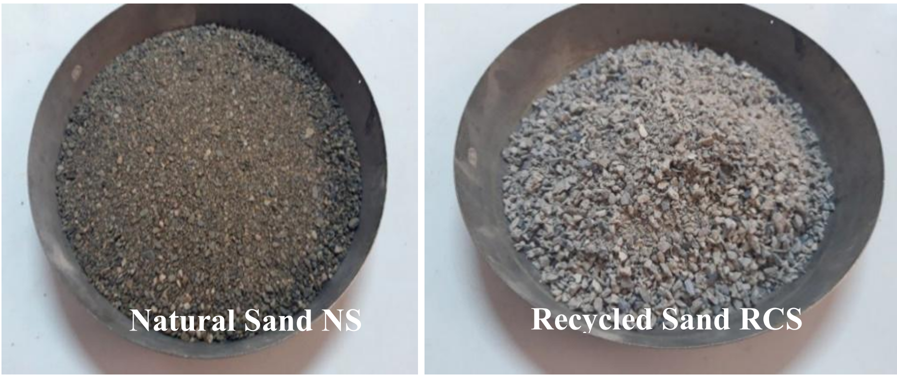

Fig. 1. View of the different sands used (NS/RCS)

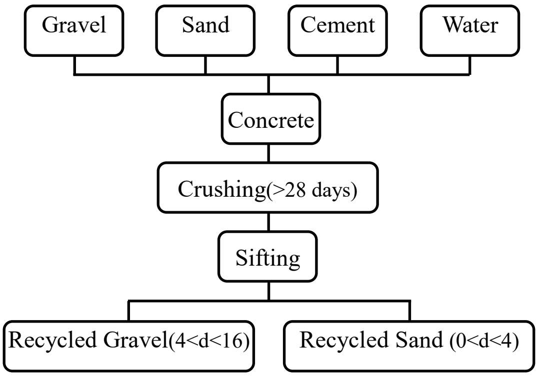

Fig. 2. RCS Manufacturing process diagram

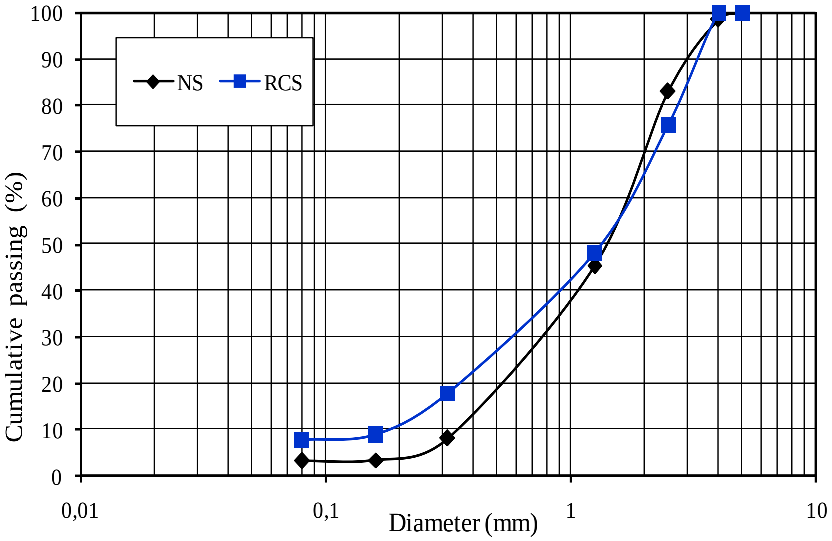

Fig. 3. Particle size curves of the two sands used

2.2. Experimental process

2.2.1. Specimens'preparation

To analyse the effect of RCS on the properties of mortars in both the fresh and hardened states, the mortars were prepared with cement-to-sand-to-water mass ratios of 1:3:0.55. Various doses of superplasticiser were added to ensure the mortars maintained a plastic consistency. The water content in the superplasticiser was subtracted from the total mixing water. Table 3 provides a summary of the compositions for each mortar.

Table 3. Mix proportion for all mortars studied for different types of tests

Mixt	Cement (g)	NS (g)	RCS (g)	RCS %	SP (%)	Water (g)
M_0	450	1350	0	0	0.5	245.92
M_{20}	450	1080	270	20	0.7	245.29
M_{40}	450	810	540	40	1	244.35
M_{60}	450	540	810	60	1.1	244.03

2.2.2. Workability

After mixing the various mortars, their fluidity was evaluated using the spreading method on a shaking table. This procedure was performed in accordance with ASTM C230 [36].

2.2.3. Setting time

The setting test was carried out according to the specifications of NF P 15-431 [37], using the Vicat apparatus. The onset of hardening is defined as the time when a significant increase in the viscosity of the paste is observed.

2.2.4 Apparent density

This involves measuring the mass per unit volume of material by eliminating all voids between the grains. The ratio of the recorded mass to the corresponding volume of the material gives the absolute density.

2.2.5 Mechanical strength

The compressive strength of all mortars was determined in accordance with the European standard EN 196-1:2016 [38]. Mortar specimens were prepared by casting 40 mm cubes. After 24 hours, the specimens were demoulded and immersed in water at 23°C. They were removed from the water one hour prior to being subjected to compressive strength testing at 1, 3, 7, and 28 days.

2.2.6. Shrinkage

Hydration shrinkage, also known as drying shrinkage, is a physical phenomenon that occurs in mortar after the setting period. It is characterised by a reduction in weight and a decrease in volume, caused by the evaporation of water retained within the pores.

The test involves casting prismatic specimens according to the Menut method (NF P 18-404) [39], incorporating a bolt to facilitate the measurement of length changes. After demoulding, the specimens are stored under ambient conditions. Variations in mass (weight loss) and length are recorded over a period of 28 days.

Shrinkage is defined by the following ratio:

$$\varepsilon = \frac{\Delta L}{L} \tag{1}$$

where: ΔL: change in length, expressed in µm, L: length between the two ends of the specimen, equal to 200 mm, ε: shrinkage strain, expressed in µm/m.

2.2.7. Weight loss

The specimens prepared in this way were then exposed to air at a temperature of 20 ± 2°C for a period of 28 days. The weight of the specimen was measured over the 28-day period. It should be emphasised that conditioning in a dry room is essential to allow water contained in non-interconnected pores to leave the specimen. Otherwise, this water would be incorrectly considered as absorbed water. The mass loss is defined by the following ratio:

$$\Delta M = \frac{M_0 - M_i}{M_0} \tag{2}$$

where: ΔM: mass loss in percentage, M_0: initial mass of the specimen, M_i: mass of the specimen on day i.

3. Test results and discussion

3.1. Fresh state

3.1.1. Effect of RCS on workability

To maintain consistent workability and ensure proper mould filling, the use of a superplasticiser was essential. It was observed that the required amount of superplasticiser increased with the substitution percentage of RCS (see Fig. 4).

This is attributed to the rough surface texture of this sand, which generates more friction between the sand grains, leading to a higher demand for superplasticiser.

Additionally, the high absorption capacity of RCS, due to its porosity, is a key factor in determining the amount of water needed for mortar hydration. As a result, the demand for superplasticiser increases with the replacement rate to compensate for the mixing water absorbed.

This observation is supported by Jang et al. [4], who found that the use of RA reduces slump values compared to control mixes. This reduction is influenced by several factors, such as the amount of attached mortar, which increases the water absorption of RA, the replacement rate, and the mix design method.

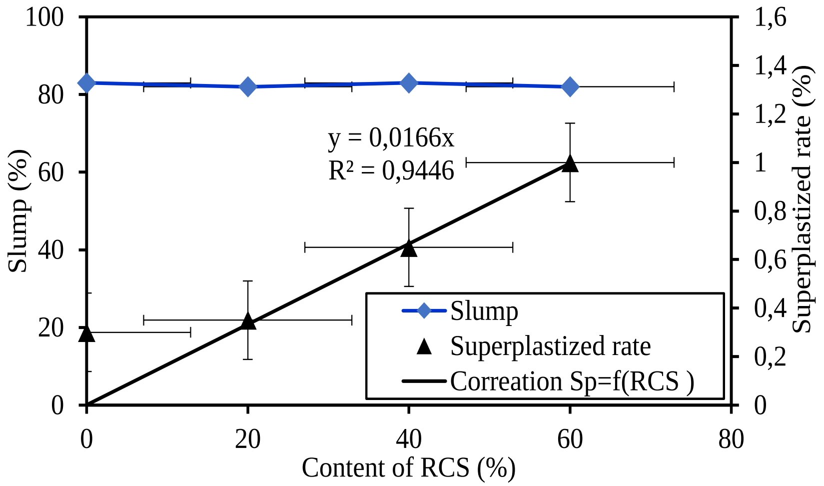

Fig. 4. Need for superplasticiser for mortar

3.1.2. Effect of RCS on apparent density

The results of the fresh-state bulk density are presented in Fig. 5. It is clearly shown that fresh-state bulk density decreases as the substitution rate of recycled sand increases. This trend is expected, as the bulk density of recycled sand is lower than that of natural sand.

This reduction is primarily attributed to the higher porosity and the presence of fine particles in recycled sand, which reduce the overall compactness of the mix. Additionally, variability in the quality of recycled sand can lead to fluctuations in the mortar's bulk density. These observations are consistent with previous research, which confirms that the use of recycled sand reduces the overall density of mortar mixes [40,21].

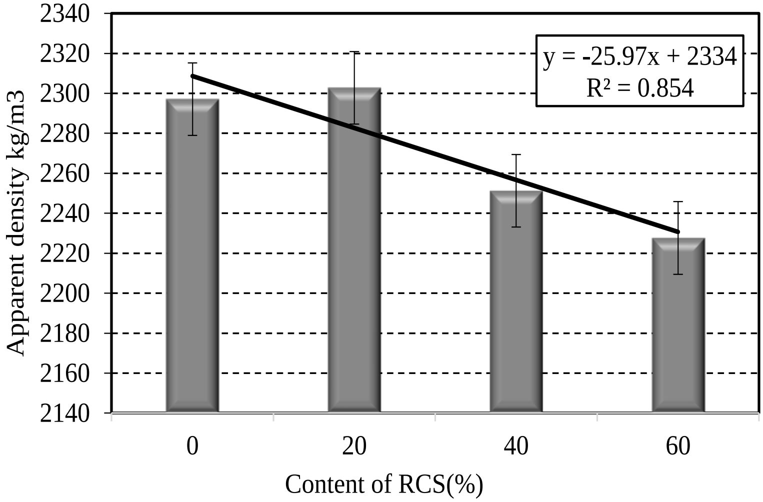

Fig. 5. Variation of apparent density depending on the rate of RCS

3.1.3. Effect of RCS on setting time

Figure 6 illustrates the initial and final setting times of mortar as a function of the replacement rate of NS by RCS. It is clearly shown 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 approximately 13.3% and 17.34% for substitution rates of 40% and 60% RCS, respectively.

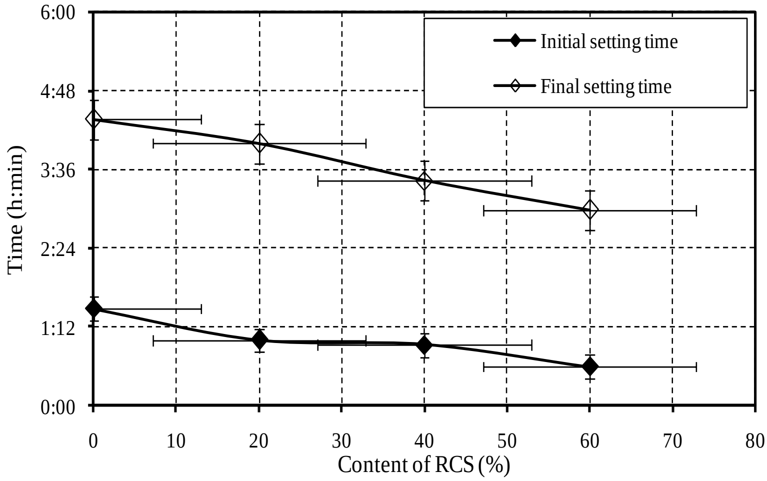

Fig. 6. Effect of CRS on initial and final setting time for cement

3.2. Hardened state

3.2.1. Effect of RCS on flexural and compressive strength

Figure 7 illustrates the evolution of mechanical strength in various mortars at 1, 3, 7, 28, and 90 days, with varying substitution rates of RCS. 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 90-day results reveals strength improvements compared to mortars formulated solely with NS: increases in compressive strength of 17.4%, 8.5%, and 15.4%, respectively, and strength gains of approximately 3%, 9%, and 12% 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.

Moreover, the use of a superplasticiser reduced the quantity of water required 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.

Previous studies [6,7,19,21] have consistently shown that incorporating RS in mortars often results in enhanced compressive strength. This improvement is particularly evident when crushed recycled sand is used as a complete replacement for natural sand (NS). The enhancement in strength can be attributed to several factors, including the angular shape and rough surface texture of RCS particles, which improve the mechanical interlock and bond with the cement matrix. Additionally, the presence of fine residual cementitious materials adhered to the RCS particles may contribute to secondary hydration.

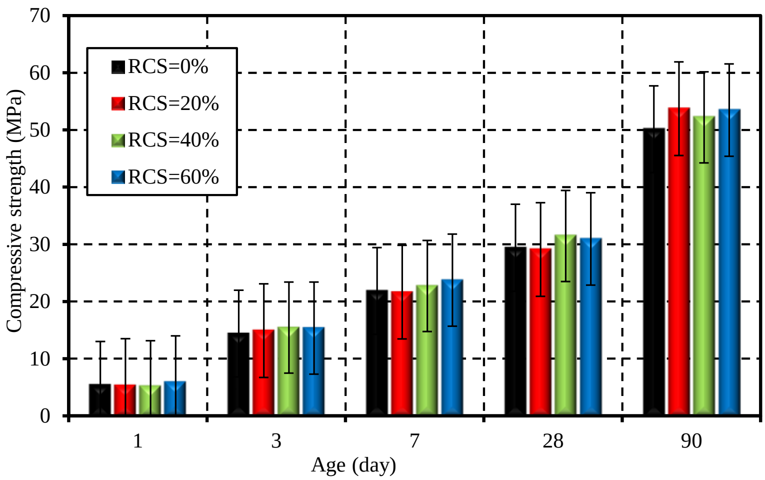

Fig. 7. Effect of RCS on compressive strength of mortar

Furthermore, according to Jang 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.

Tang et al. [41] found that replacing 25% of natural aggregates with recycled aggregates increased tensile strength by approximately 20%.

This result confirms the observations of Seethapathi et al. [42], who noted that incorporating 30% recycled aggregates into self-compacting concrete (SCC) improved tensile strength by 18.48% after 28 days.

Figure 8 shows the progressive increase in flexural strength over time, up to 28 days, for different mortars made with varying proportions of recycled sand.

The illustrated results clearly indicate that this evolution is influenced by the amount of recycled sand used. It is observed that the presence of recycled sand significantly improves flexural strength, surpassing that of mortars made with natural sand as early as the third day. This finding confirms the positive impact of recycled sand on the development of mechanical strength.

These results are consistent with those reported by [43,21,3], who observed that the flexural strength of mortars containing recycled sand is higher than that of mortars made with natural sand. Additionally, the hydration process can affect the characteristics of cement powder in both fresh and hardened states, such as compressive strength [44].

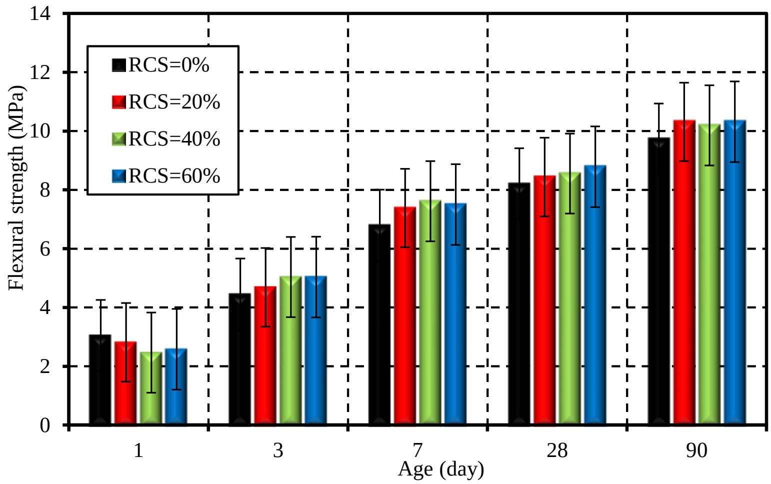

Fig. 8. Effect of RCS on flexural strength of mortar

3.2.2. Effect of RCS on shrinkage

Figure 9 illustrates the shrinkage evolution for each specimen, where the influence of RCS sand appears to be predominant. As the RCS content in the mortar increases, shrinkage intensifies due to the high porosity and deformability of RCS sand compared to natural sand. The most significant increase in shrinkage occurs within the first 30 days, after which it tends to level off, especially at lower RCS percentages. Additionally, the error bars are relatively small, indicating consistent results with minor experimental variability.

Similar studies [45,46] have shown that increasing the substitution rate of NS with RCS sand leads to significant shrinkage, likely attributable to the high porosity of RCS and the strong water absorption capacity of the original mortar coating these aggregates.

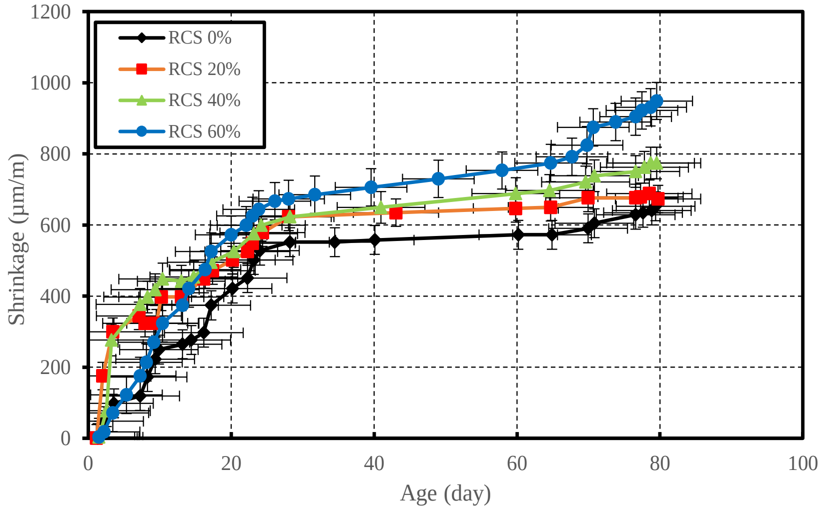

Fig. 9. Effect of RCS on the evolution of shrinkage

These observations align with findings from other researchers [47,48], who concluded that the use of recycled aggregates has a significant impact on shrinkage kinetics. They attributed this increase to the high absorption caused by the material's high porosity, which accelerates desiccation. Additionally, the old attached mortar continues to shrink, further increasing the total shrinkage of the new mortar and/or concrete.

Ait Mohamed Amer et al. [43] observed that the effect of recycled aggregate on shrinkage is negligible when the water-to-cement (W/C) ratio is low (0.4), as shrinkage stabilises and eventually becomes comparable to that of the reference concrete over time. However, when the W/C ratio increases to 0.5 and 0.6, the effect becomes more pronounced and grows significantly with the increasing percentage of recycled aggregates (RA).

3.2.3 Effect of RCS on weight loss

Figure 10 presents the results of weight loss tests on mortars with different RCS ratios, measured over time. It is observed that all mixes exhibit rapid weight loss in the first 10 days, and after 28 days, weight loss stabilises between 4% and 5%. The substitution of NS with RCS sand leads to a slight increase in weight loss.

During setting, the water used for workability is retained in the capillary pores of the cement paste. Over time, this water evaporates, resulting in weight loss in mortars and concrete. RCS sand accelerates weight loss due to its high porosity and its residual mortar content, which becomes fully saturated with water during mixing. Weight loss is more pronounced in the first few days and stabilises after the second week.

The increased weight loss due to evaporation is consistent with the higher shrinkage observed in the previous figure (see Fig. 9). This weight loss is likely attributable to the evaporation of moisture from the cementitious matrix.

Similar results were reported by other researchers [47-49], who confirmed that incorporating recycled aggregates into concrete significantly increases weight loss.

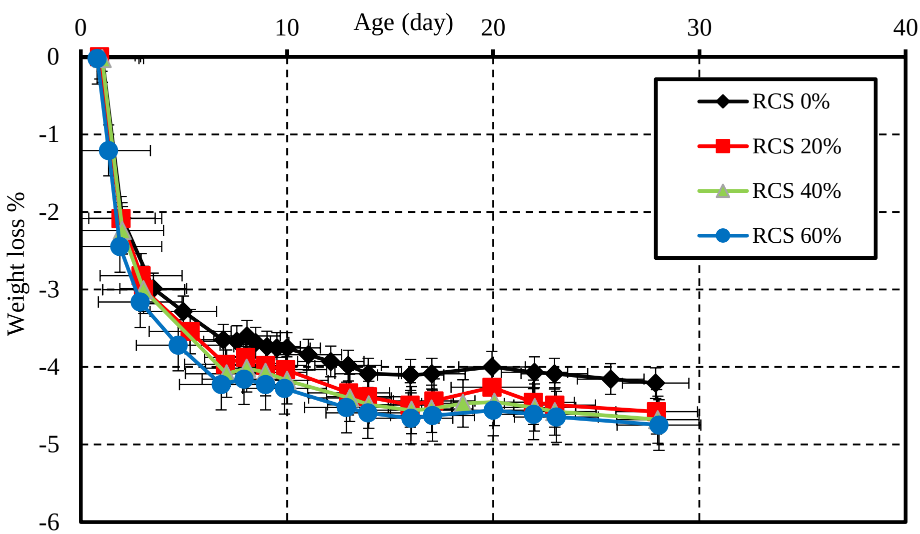

Fig. 10. Effect of RCS on the variation of the weight loss

4. Conclusions

The present study aims to produce an economical and eco-friendly material by substituting NS with 20%, 40%, and 60% RCS from demolished concrete in mortar production.

Based on the experimental protocol used and the results obtained, the following conclusions can be drawn:

1. RCS from demolished concrete can be successfully used in the production of plastic mortars without compromising their basic integrity.
2. Increasing the RCS content results in a noticeable reduction in the plasticity and workability of the mortar. This reduction necessitates a higher dosage of superplasticiser to achieve the desired workability levels, particularly at substitution rates of 40% and 60%.
3. The incorporation of RCS beyond 20% leads to a decrease in the apparent density of the mortar. This is primarily attributed to the higher porosity and increased water absorption capacity of RCS compared to natural sand.
4. It is clearly shown that the setting time decreases inversely with the substitution rate of NS by RCS. This reduction is primarily attributed to the presence of anhydrous cement grains from the old mortar attached to RCS grains.
5. The use of RCS in mortar improves compressive strength. This enhancement is likely due to the presence of residual anhydrous cement on the surface of RCS particles and the rough texture of the grains, which promotes better bonding with the cement matrix.
6. When the quantity of RCS exceeds 20%, it significantly increases drying shrinkage and mass loss in mortars. These effects are primarily related to the porous structure and highwater absorption of the RCS, which influence the water retention and moisture loss characteristics of the mortar over time.

Conflict of interest

The authors declare that they have no conflict of interest.

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