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Sustainable Utilization of Recycled Concrete Powder as Sand Replacement in Cement Mortar Production: Impact of Sand-Cement Ratio

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Abstract

The construction industry is becoming more interested in recycled concrete sand obtained from concrete waste due to the urgent need for environmentally friendly building materials. This research investigates the mechanical along durability properties of cement mortars made of recycled concrete sand as a full replacement of natural sand. With a fixed water-to-cement ratio of 0.48, five values of sand-to-cement ratio, including 0.50, 1.00, 1.50, 2.00, and 2.75, were used to prepare different mortar mixes to investigate its effect on the behavior of the mortar. Results indicate a decline in workability with an increasing sand-to-cement ratio, with flow values ranging from 137% at a sand-to-cement ratio of 0.5 to 58% at a sand-to-cement ratio of 2.75. The highest compressive strength of 40.3 MPa was observed in the mix with a sand-to-cement ratio of 0.5 at 28 days, while the mix with a sand-to-cement ratio of 2.75 exhibited the lowest strength at 29.8 MPa, attributed to higher internal porosity. The mix of sand to cement of 1.5 demonstrated a balanced performance, achieving a compressive strength of 29.8 MPa and a flow value of 110 ± 5%, making it suitable for practical applications. Water absorption increased with higher sand-to-cement ratios, consistent with increased void content. Microstructural analysis revealed the presence of residual cementitious phases such as belite and calcium hydroxide in recycled concrete sand, contributing to secondary hydration and influencing durability characteristics. Although mortars containing natural sand outperformed recycled concrete sand-based mixtures in strength and workability, recycled concrete sand mortars met the required performance criteria for building, plastering, and non-structural applications. This study supports the viability of recycled concrete sand as a sustainable alternative to natural sand, contributing to resource conservation and waste reduction in the construction industry.

Keywords: Recycled Concrete Sand; Sand-to-Cement Ratio; Concrete Waste; Physical-Mechanical Properties; Microstructural Analysis.

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1. Introduction

Cement mortar is a composite mixture of cement, sand, and water. It is used in various applications, including masonry blocks and plastering. Sand is a crucial component in mortars, significantly influencing on mortar properties and performance. The primary role of sand is to add volume and fill gaps between cement particles, resulting in a compact and homogeneous mixture. It improves the compressive and flexural strength of the mortar while also increasing its durability by minimizing shrinkage and cracking. The appropriate selection and use of sand are essential for attaining a good mortar mix. The proportions of sand utilized in mortar influence workability, durability, and mechanical strength in construction applications. The amount of water used during the mixing process influences both the setting and hardening characteristics of mortar, as well as fundamental properties throughout the process [1, 2].

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Materials engineers must carefully select sand-to-cement ratios for mortar applications [3, 4]. The cost of the mortar mix decreases as the sand content increases. Masonry mortars require low S/C ratios to achieve maximum strength [5]. Furthermore, key properties of cement mortar-such as workability, porosity, specific gravity, density, water absorption and compressive strength, respond sensitively to the S/C ratio [6]. However, lower sand content requires a higher cement dosage to enhance adhesion and strength. Conversely, excess sand can reduce cohesion due to insufficient cement to bind the mixture [2]. Also, the modulus ratio is a critical factor affecting the behavior of mortars when utilizing natural aggregates, as indicated by recent studies [3, 7].

Numerous studies have investigated the influence of sand content and aggregate properties on mortar or concrete performance. For example, Alarab et al. [1] investigated how different cement-to-sand ratios (1:0.45 and 1:0.83 vs cement) affect mortar mechanical properties and sustainability performance. They found that as the S/C ratio increased, compressive strength decreased by 41.5% and 28.2%, respectively, compared to cement mortar, while flexural strength improved slightly. The higher sand content necessitated more water to maintain workability, confirming that increasing S/C ratio compromises strength and demands careful water management. Also, De Larrard & Belloc [8] conducted experiments in which they controlled aggregate content while maintaining consistent grading and matrix composition to prevent segregation, and Stock et al. [9] reviewed the impact of aggregate volume on the compressive strength, the results suggest that the strength of cement paste in compression is reduced by the addition of 20% by volume of graded aggregate, falling to a minimum value at a volume fraction of 30 to 35% and then increasing with further addition of aggregate. As Yang & Huang [10] showed, the compressive strength of mortar and concrete strongly depends on the same properties and volume fraction of aggregates and confirming their crucial role in overall strength development. Fu et al. [11] observed that compressive, splitting tensile, and flexural strengths increase with more binder. Perry and Gillott [12] and Chen et al. [13] experimentally confirmed that the type of aggregate significantly influences mortar strength.

However, natural sand sources have been depleted, and there are growing environmental concerns, which have attracted recycled concrete sand obtained from crushed concrete waste as an alternative to natural sand in mortar production. Although recycled concrete sand contains crushed cement paste and fine aggregates, this combination has been shown to enhance mechanical performance compared to natural sand. Recycled concrete sand is more porous and water-absorbent than natural sand, as noted in recent studies [14-17]. The presence of residual cementitious materials in recycled concrete sand leads to a higher surface area and increased water absorption, necessitating strict control of the water-to-cement (w/c) ratio to prevent excessive drying and shrinkage [18]. Thermal analysis and X-ray diffraction (XRD) of recycled concrete sand confirm the presence of unhydrated cementitious phases that can negatively impact durability and long-term strength retention [19].

Several researchers suggest that recycled concrete sand may be included in masonry mortars [20-23]. Most research shows that the masonry mortar mechanical strength decreases as the % of recycled concrete sand increases [22, 24]. Silva et al. study emphasizes that the compressive performance of the composite is more closely linked to the compressive strength of the aggregate than to the bond between the cement matrix and the interfacial transition zone (ITZ) [25]. Due to adhering mortar and inherent porosity, recycled concrete aggregates typically exhibit inferior mechanical properties compared to natural aggregates [26, 27]. Also, a reduction in mortar density as a function of increasing recycled concrete sand content has also been reported [28-30].

Several studies shows that when RCA particles are incorporated into plastering at a substitution level of 20-25%, the compressive strength either slightly increases or remains consistent to that of control mortar mixes. This was also highlighted in study conducted by previous studies [31-36]. The study by Mardani-Aghabaglou et al. in 2019 delves deeper into this subject [37]. Their findings show that when the percentage replacement of RCA is restricted to 25%, the strength of the mortar remains largely on par with mortar mixes made using natural river sand. Additionally, various studies on the compressive, split tensile, and flexural strengths of concrete incorporating recycled concrete sand have shown improvements when up to 60% of the natural fine aggregates are replaced [35]. Another study done by Kępniak & Łukowski [38], this study examined mortars with 0-100% recycled concrete sand (RCS), keeping a fixed cement content and varying the sand proportion. Results showed that as the sand-to-cement ratio increased, compressive strength declined up to 20%, while workability decreased and water absorption increased. However, the optimal replacement level of natural sand with recycled sand is between 40% and 60%, as it provides satisfactory flexural and compressive strengths.

However, a pivotal observation is that as the RCA substitution reaches its maximum at 100%, there's a drastic dip in the mortar's strength [37]. This is primarily because recycled waste-based mortar has a high water-cement ratio. Despite these findings, the effect of the sand-to-cement (S/C) ratio on mortars with 100% replacement of natural sand by recycled concrete sand remains underexplored. The use of fully recycled concrete sand poses technical challenges, including higher porosity, increased water demand, reduced workability, and lower mechanical strength. Although previous research has addressed some of the mechanical and durability issues associated with 100% recycled concrete sand, no systematic studies have focused on identifying the optimal S/C ratio. Understanding this gap is critical to improving workability, strength, density, and absorption properties in practical applications.

1.1. Research Novelty and Objective

This study investigates the mechanical, durability, and microstructural properties of cement mortars containing 100% recycled concrete sand (RCS) derived from concrete waste, with varying sand-to-cement (S/C) ratios while maintaining a constant water-to-cement (w/c) ratio. Although recycled concrete sand has been previously used in mortar production, no study has systematically examined the influence of the S/C ratio on the performance of mortars made entirely with RCS to identify the optimal mix design for practical use. To address this gap, the present work aims to determine the optimal S/C ratio for producing high-performance and sustainable mortar using 100% recycled concrete sand. The experimental methodology is outlined in the flowchart shown in Figure 1.

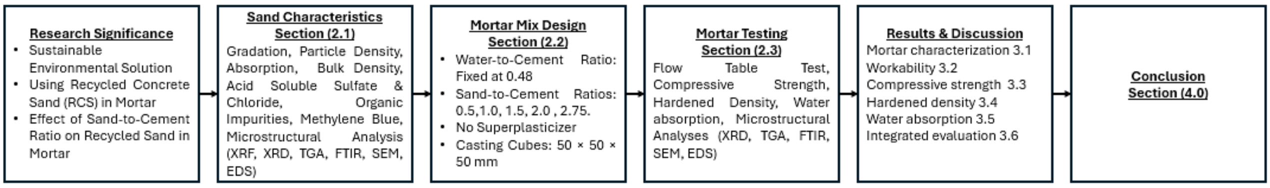


Figure 1. Flowchart of the research

2. Materials and Methods

2.1. Materials Characterization

Ordinary Portland cement (OPC), water, commercially available washed sand (WS), and recycled concrete sand (RCS) derived from concrete waste were used in this study to prepare the cement mortar mixtures. OPC with a strength class of 42.5 N, in accordance with BS EN 197-1, was utilized. The recycled concrete sand was sourced from a recycling facility in Qatar and was composed of waste generated by ready-mix concrete manufacturers. This waste underwent screening, crushing, and sieving processes, resulting in various particle size fractions. The fine fraction with a particle size of 0-5 mm was selected and classified as recycled concrete sand. Figure 2 shows photographs of both washed sand (WS) and recycled concrete sand (RCS).

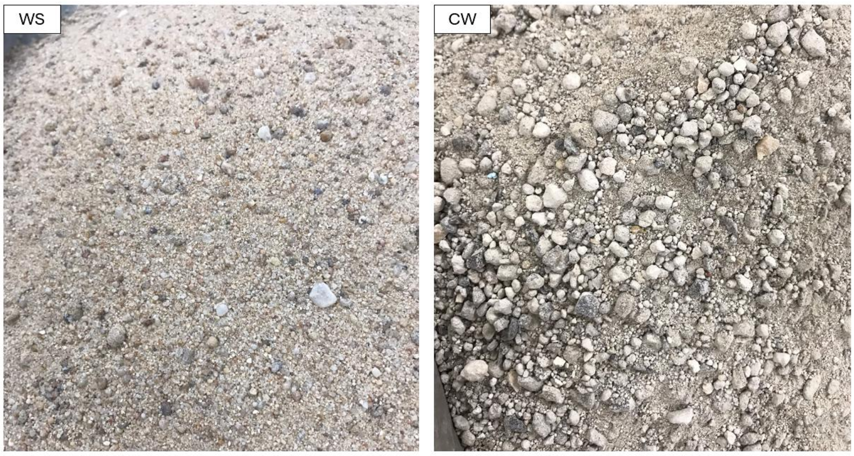


Figure 2. Washed sand (WS) and recycled concrete sand (RCS)

Before its use, the recycled concrete sand (RCS) underwent comprehensive characterization to evaluate its technical properties. Its gradation and suitability for mortar applications were compared against the minimum and maximum limits specified in ASTM C144, as shown in Figure 3. ASTM C144 defines the nominal particle size requirements to ensure proper workability, strength, and durability of masonry mortar. The gradation curve of the washed sand (WS) falls within the well-graded range, making it suitable for mortar production. In contrast, the RCS curve exhibits a steeper slope, indicating a higher proportion of fine particles passing the 0.3 mm sieve, which may lead to increased water demand, reduced workability, and higher shrinkage. Additionally, WS displays a more uniform particle size distribution across all sieve sizes, while RCS shows a deficiency in coarse fractions, particularly those above 0.6 mm.

The main physical, mechanical, and chemical properties of both sand types are summarized in Table 1. Compared to WS, RCS exhibits significantly higher water absorption (17.50% vs. 2.20%), lower dry specific gravity (2.115 vs. 2.560), and lower bulk density (1480 vs. 1670 kg/m³), reflecting its lower packing density and increased water requirement. Due to the variable nature of RCS, the presence of adhered cementitious paste, and its high content of fine particles (below 250 µm), accurate water absorption testing remains challenging [39]. These results are consistent with findings reported in previous studies [40, 41].

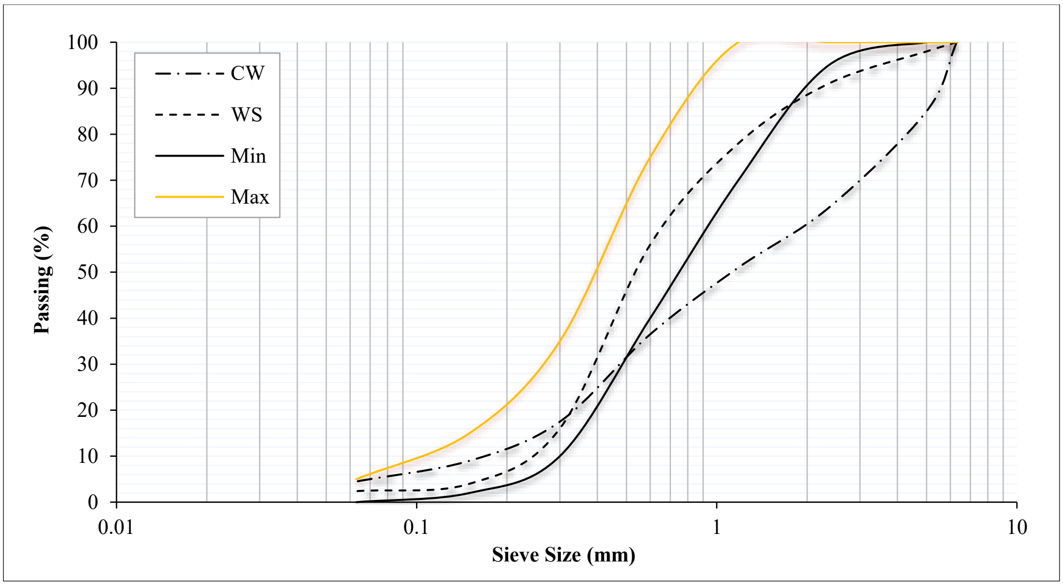


Figure 3. Grading curves of sands

Table 1. Quality properties of sand

Test No.	Test Description	Method	Quality Properties	
			WS	RCS
		Physical Tests		
1	Absorption %	EN 1097-6:2013	2.20	17.50
2	Oven Dry SG	EN 1097-6:2013	2.560	2.115
3	SSD SG	EN 1097-6:2013	2.620	2.480
4	Apparent SG	EN 1097-6:2013	2.720	2.610
5	Bulk Density (Rodding) Kg/m^3	ASTM C29	1670	1480
6	Bulk Density (Shoveling) Kg/m^3	ASTM C29	1530	1350
		Chemical Tests		
7	Acid soluble sulfate %	BS EN 1744-1	0.28	1.25
8	Acid soluble chloride %	BS EN 1744-5	0.01	0.01
9	Organic Impurities	ASTM C40	NILL	NILL
10	Methylene Blue	BS EN 1097-6	0.4	1

The higher water absorption of RCS compared to natural sand is primarily attributed to its porous microstructure and production method [40, 41]. The particles of recycled sand differ in shape and surface texture, leading to increased surface area and higher water retention [40]. Furthermore, recycled sand sourced from demolished concrete may contain residual binders and cementitious materials, which contribute to its water absorption capacity [42].

The X-ray fluorescence (XRF) analysis results presented in Table 2 reveal a significant compositional difference between recycled concrete sand (RCS) and washed sand (WS), particularly in terms of calcium oxide (CaO) and silicon dioxide (SiO_2) content. RCS exhibits a high CaO concentration of up to 59.9%, compared to 19.9% in WS. This elevated CaO level in RCS is attributed to the presence of residual cement paste and un-hydrated cement particles. In contrast, WS contains a substantially higher proportion of SiO_2, measured at 67.36%, while RCS contains only 18.13%.

Table 2. Chemical composition of sand

Material	SiO_2	Al_2O_3	CaO	Fe_2O_3	SO_3	MgO	K_2O
RCS	18.13	4.49	59.9	5.5	4.78	5.31	0.62
WS	67.36	3.78	19.9	1.94	4.61	1.34	1.45

The high silica content in WS is typical of natural sands, contributing to its inert behavior and stability as a fine aggregate. This contrasts with RCS, which contains reactive cementitious components that may actively influence the chemical and mechanical performance of mortar mixtures. These findings suggest that while WS primarily acts as an inert filler, RCS may provide additional reactivity and binding potential due to its residual cementitious materials.

The mineralogical composition of the sand samples was determined using X-ray diffraction (XRD), as shown in Figure 4. The analysis was conducted using CuKα radiation ($\lambda = 1.54$ Å), with scans performed over a 2θ range of 5° to 50°, in 2° steps, at a rate of 2 seconds per step. The XRD patterns of washed sand (WS) and recycled concrete sand (RCS) reveal notable mineralogical differences, which can significantly influence the performance of mortar at different sand-to-cement (S/C) ratios.

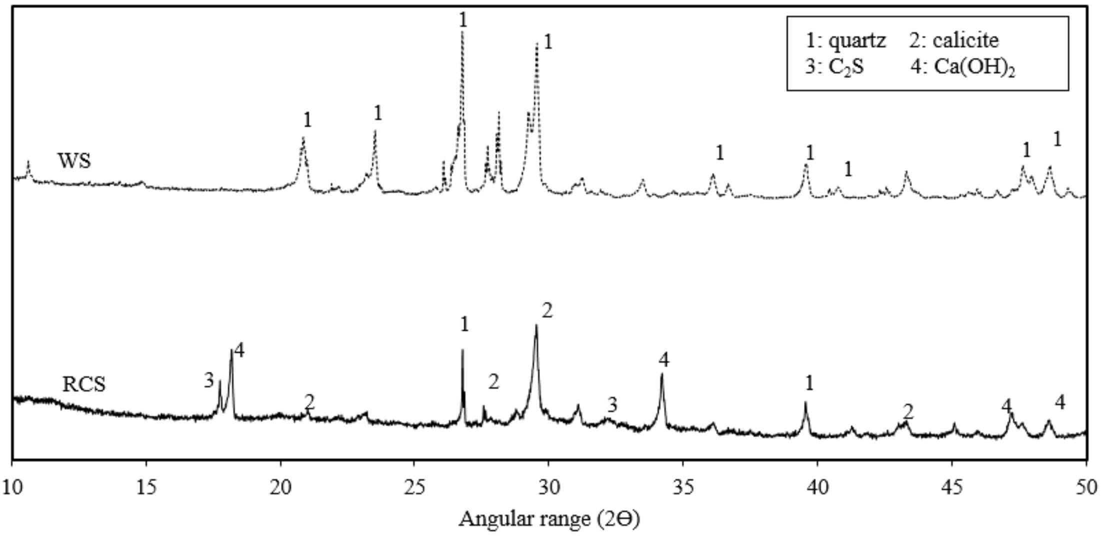


Figure 4. XRD analysis for sand

In general, WS is primarily composed of quartz (SiO_2), a stable and inert mineral that does not interfere with cement hydration. In contrast, RCS contains residual cementitious phases originating from its parent concrete, including dicalcium silicate (C_2S), portlandite [$Ca(OH)_2$], and calcite ($CaCO_3$). These compounds can negatively impact strength development, increase water demand, and reduce workability. Therefore, careful proportioning of the S/C ratio is necessary to optimize workability, mechanical performance, and overall durability.

Further analysis of the RCS diffraction pattern shows several peaks in the 27°-30° range, corresponding to quartz (SiO_2) and calcite ($CaCO_3$), indicating the presence of both natural aggregates and cementitious phases. The presence of calcite suggests the existence of cement hydration products such as calcium silicate hydrate (C-S-H) and calcium hydroxide (C-H), which contribute to the residual strength of RCS [43]. The broad diffraction peaks also indicate the presence of both crystalline and amorphous phases within the recycled material.

Figure 5 illustrates the thermal stability differences between washed sand (WS) and recycled concrete sand (RCS), as observed through thermogravimetric analysis (TGA). The decomposition behavior of the two materials varies significantly due to their distinct compositions. WS shows minimal mass loss, primarily attributed to the evaporation of surface moisture below 150 °C. This is consistent with its predominantly siliceous (SiO_2) and thermally stable nature.

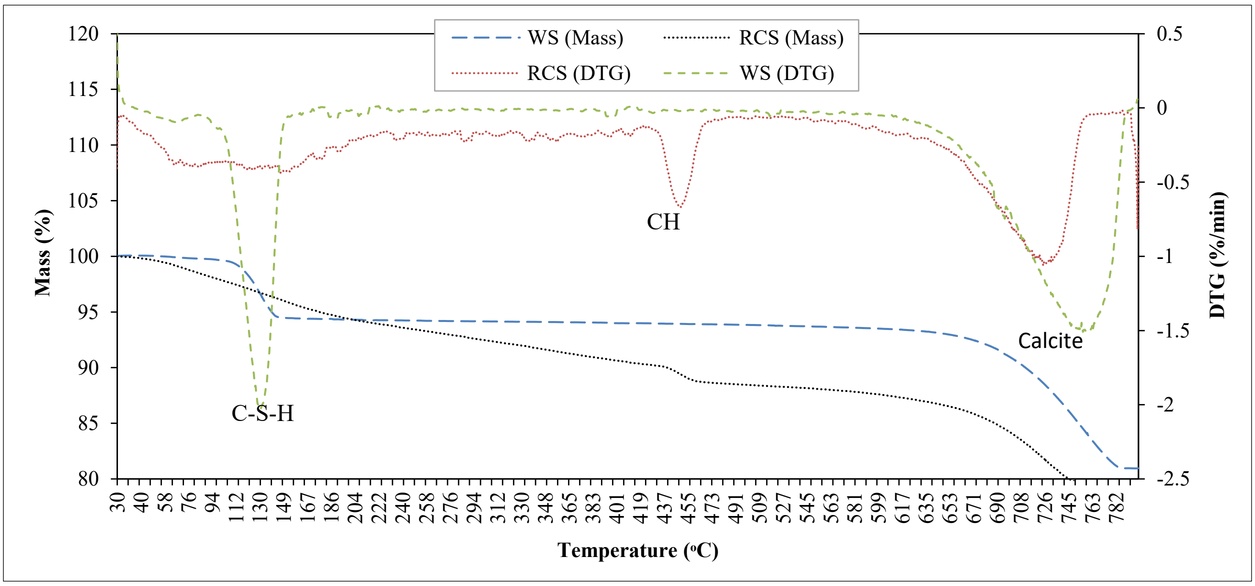


Figure 5. TGA results of sand

In contrast, RCS exhibits significant mass losses across various temperature ranges due to the presence of hydrated cementitious phases. The initial weight loss observed below 150 °C corresponds to the evaporation of free and physically adsorbed water [44, 45]. A major mass loss occurring between 400-500 °C is associated with the decomposition of portlandite [$Ca(OH)_2$] [19, 46, 47]. Furthermore, a substantial mass reduction between 600-750 °C is attributed to the decomposition of calcium carbonate ($CaCO_3$) into calcium oxide (CaO) and carbon dioxide (CO_2), confirming the presence of residual cementitious compounds in RCS [44].

Figure 6 presents the Fourier-transform infrared (FTIR) spectra of recycled concrete sand (RCS) and washed sand (WS). The spectrum of RCS displays distinct absorption bands indicative of both hydrated and unreacted cementitious compounds, including water, carbonates, sulfates, and silicates. A broad absorption band above 1600 cm^{-1} corresponds to bound water and hydroxyl groups, originating from hydration products. The absorption band near 1400 cm^{-1} is attributed to carbonates, primarily calcium carbonate, which forms as a result of cement hydration. Furthermore, a band around 1100 cm^{-1} is associated with sulfate groups, while the overlapping peak near 1000 cm^{-1} corresponds to Si-O stretching vibrations, characteristic of both quartz and cementitious silicate phases.

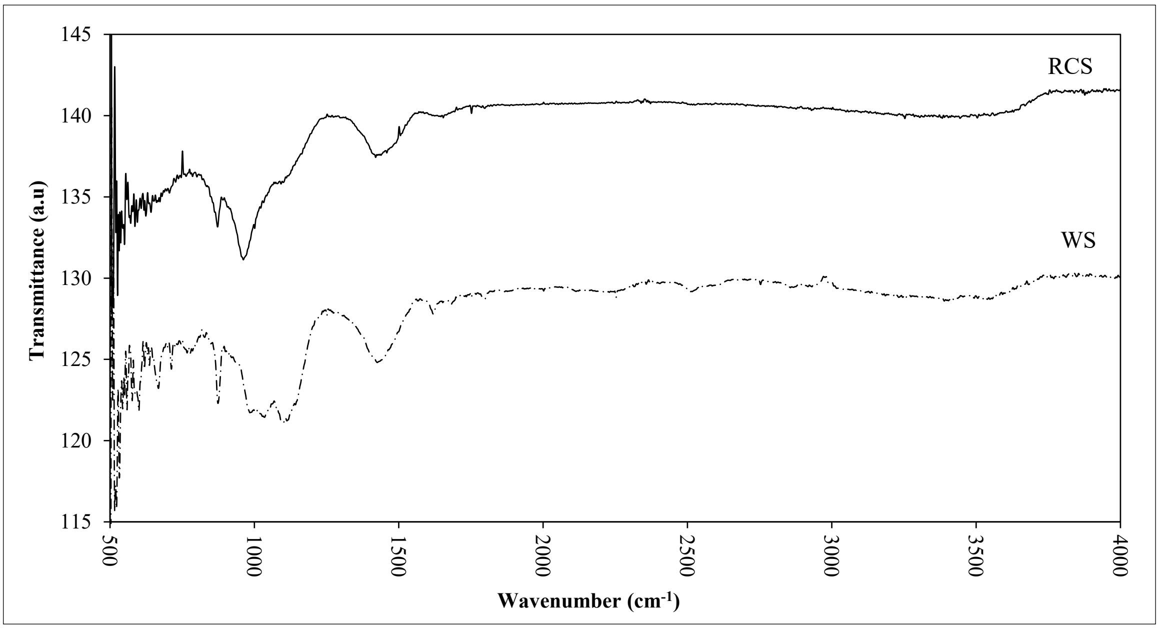


Figure 6. FTIR spectra for sand

In contrast, the FTIR spectrum of WS primarily exhibits a strong silicate band, confirming its quartz-dominant composition. This clear spectral distinction between WS and RCS indicates that RCS contains active cementitious phases, which may influence the hydration process, workability, and overall performance of mortar mixtures-particularly as the sand-to-cement (S/C) ratio varies.

The microstructure of washed sand (WS) and recycled concrete sand (RCS) was examined using scanning electron microscopy (SEM), as shown in Figure 7. The WS particles exhibit a needle-like and angular morphology, resulting in a high degree of interlocking due to their sharp edges. This interlocking restricts the smooth movement of particles, often necessitating the addition of water or chemical admixtures to overcome these sharp edges and enhance workability.

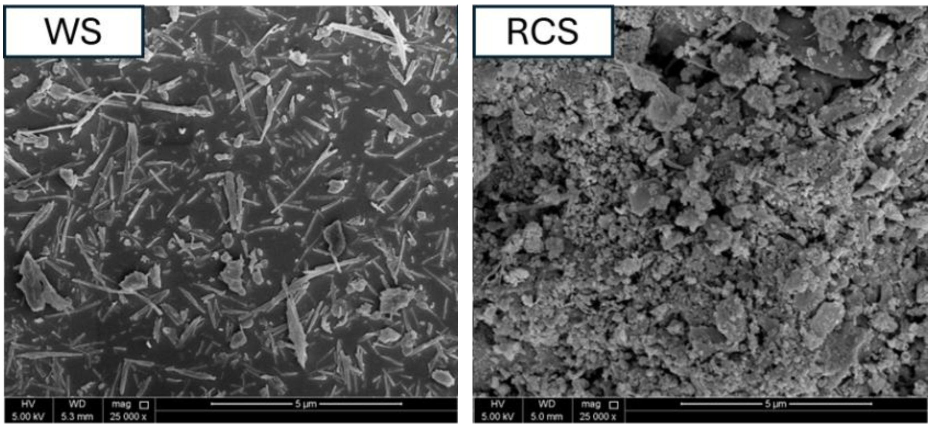


Figure 7. SEM for sand

In contrast, RCS consists of rounded and smoother particles, which significantly improve workability by reducing internal friction and promoting better particle packing. The rounded morphology of RCS facilitates improved mixing, compaction, and flowability, making it particularly suitable for applications requiring high workability. However, RCS typically contains remnants of old concrete mortar adhered to its grains, including calcium silicate hydrate (C-S-H) gel and portlandite [$Ca(OH)_2$], which can affect its properties. These residual cementitious materials are porous and contribute to higher water absorption.

2.2. Mortar Preparation and Mix Design

The experimental program was designed to investigate the effect of the sand-to-cement (S/C) ratio on mortar properties. To ensure consistency with ASTM C109 standards and eliminate the influence of water content, the water-to-cement (w/c) ratio was fixed at 0.48. The study focused on two types of sand-recycled concrete sand (RCS) and washed sand (WS)-each used as a full (100%) replacement in the mix. The impact of sand content was evaluated by varying the S/C ratio at 0.50, 1.00, 1.50, 2.00, and 2.75, as summarized in Table 3. None of the mixes contained superplasticizers or chemical admixtures.

Table 3. Mortar mixture proportions

Mix ID		Water to cement ratio (w/c)	Sand to cement ratio (S/C)	Water (kg/m^3)	Cement (kg/m^3)	WS (kg/m^3)	RCS (kg/m^3)
WS	WS 0.5	0.48	0.50	484	1000	500	0
	WS 1.0		1.00	484	1000	1000	0
	WS 1.5		1.50	484	1000	1500	0
	WS 2.0		2.00	484	1000	2000	0
	WS 2.75		2.75	484	1000	2750	0
CW	CW 0.5		0.50	484	1000	0	500
	CW 1.0		1.00	484	1000	0	1000
	CW 1.5		1.50	484	1000	0	1500
	CW 2.0		2.00	484	1000	0	2000
	CW 2.75		2.75	484	1000	0	2750

Mixing was performed in accordance with ASTM C305 to ensure uniformity. The dry components, cement and sand, were thoroughly blended before adding water, and the mixture was stirred until a consistent and homogeneous texture was achieved. To minimize variability, each mix was cast into cubes measuring 50 mm × 50 mm × 50 mm, following ASTM C109 specifications. After 24 hours, the specimens were demolded and cured in water at 23 ± 2°C until the designated testing age.

2.3. Mortar Test Procedures

The flow table test (ASTM C1437) was used to evaluate the workability of fresh mortar. The test involved pouring lean cement mortar into a mold and compacting it in two layers. After 25 drops within 15 seconds, the spread was measured one minute later to assess the mortar's flowability. To determine compressive strength, tests were conducted on 7 and 28 days using a CONTROLS machine at a loading rate of 900 to 1800 N/s, following the ASTM C109 standard. Three specimens were tested at each age, with the average value reported. The specimens were 50 mm × 50 mm × 50 mm cubes, and their hardened density was calculated by dividing the average mass of 50 specimens by their volume. Water absorption (ASTM C1403) was determined by drying the samples at 105 ± 5°C to obtain a constant mass (M_1). The samples were then immersed in water for 24 ± 0.5 hours, and the saturated mass (M_2) was recorded. The water absorption percentage was calculated as $(M_2\text{-}M_1) / M_1 \times 100$. For a more in-depth analysis, RCS 1.5 and RCS 2.75 mortars were characterized using numerical techniques such as Scanning Electron Microscopy (SEM), Fourier Transform Infrared Spectroscopy (FTIR), Thermogravimetric Analysis (TGA), and Differential Thermogravimetry (DTG) as explained in [48-51]. The RCS 1.5 mix was selected as the optimal balance of workability and strength, compared to RCS 2.75, to investigate the effects of increasing sand content on mortar properties.

3. Results and Discussion

3.1. Mortar Characterization

SEM images of recycled concrete sand (RCS) mortars with sand-to-cement (S/C) ratios of 1.5 and 2.75, presented in Figure 8, reveal notable microstructural differences. The RCS mortar with a lower S/C ratio of 1.5 exhibits a denser and more compact matrix, characterized by abundant hydration products such as ettringite, which likely contribute to higher strength. In contrast, the RCS mortar with a higher S/C ratio of 2.75 shows a more porous microstructure with increased voids and reduced cement paste coverage, which can adversely affect the material's overall strength.

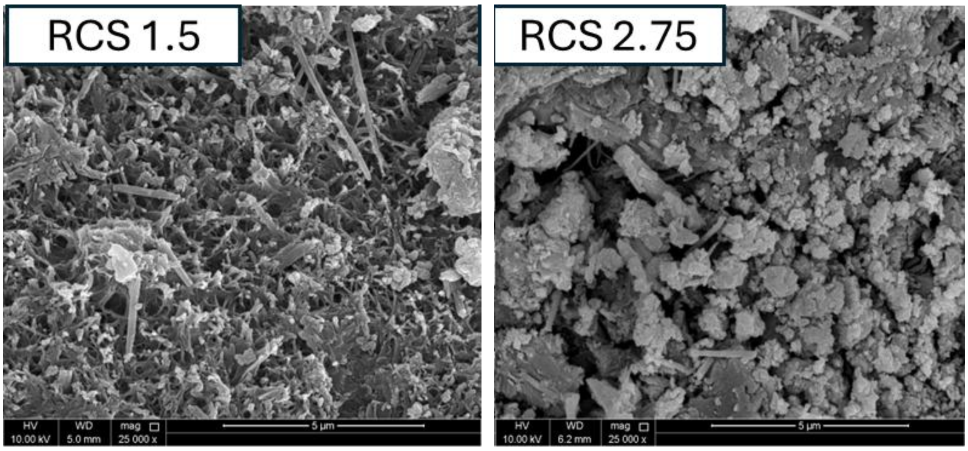


Figure 8. SEM for RCS mortar

The residual cementitious materials in RCS play a critical role in secondary hydration reactions that influence bonding and durability. The improved strength observed in the RCS 1.5 mix is attributed to the higher cement paste content, resulting in a denser matrix with plentiful hydration products including calcium silicate hydrate (C-S-H) and ettringite [52]. Conversely, the RCS 2.75 mix contains a higher proportion of sand, reducing the available cement paste to bind the particles, thereby producing a more porous structure with greater void content and decreased compressive strength.

Figure 9 shows the FTIR spectra of RCS mortars with sand-to-cement (S/C) ratios of 1.5 and 2.75, highlighting differences in hydration due to varying S/C ratios. The FTIR spectra reveal key differences that may impact compressive strength. The prominent silicate peak between 1000 and 1150 cm^{-1} in both spectra corresponds to Si-O stretching vibrations, indicating the presence of silicate phases fundamental to strength development in cementitious materials. The intensity and consistency of these peaks suggest that both mixes contain similar amounts of quartz and silicate compounds, which are essential for forming calcium silicate hydrate (C-S-H), the primary strength-giving phase in mortar.

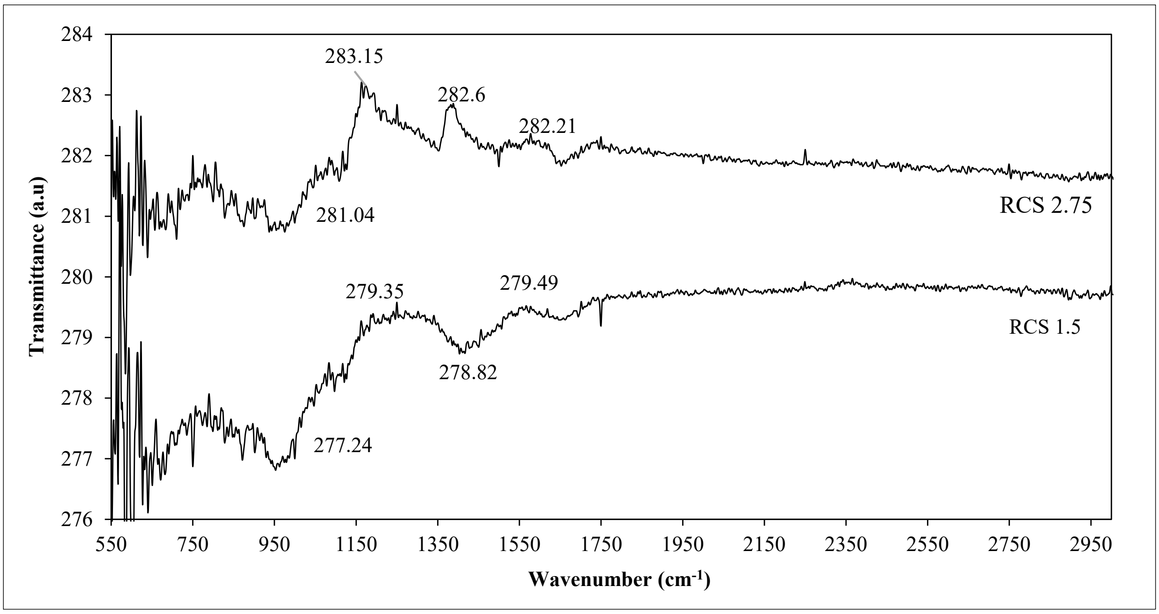


Figure 9. FTIR of RCS mortar

The broad peaks around 1600 cm^{-1} correspond to O-H stretching vibrations, indicative of bound water and hydration products. The similar intensity of these peaks in both RCS 1.5 and RCS 2.75 implies comparable hydration levels, although the density and compactness of the hydration products differ. Similarly, Figure 10 presents the TGA/DTG curves of RCS 1.5 and RCS 2.75, which exhibit high similarity, suggesting analogous thermal decomposition behavior in both materials. These similarities imply that both samples retain substantial quantities of cementitious material, with residual hydration products existing alongside cement in the mixtures.

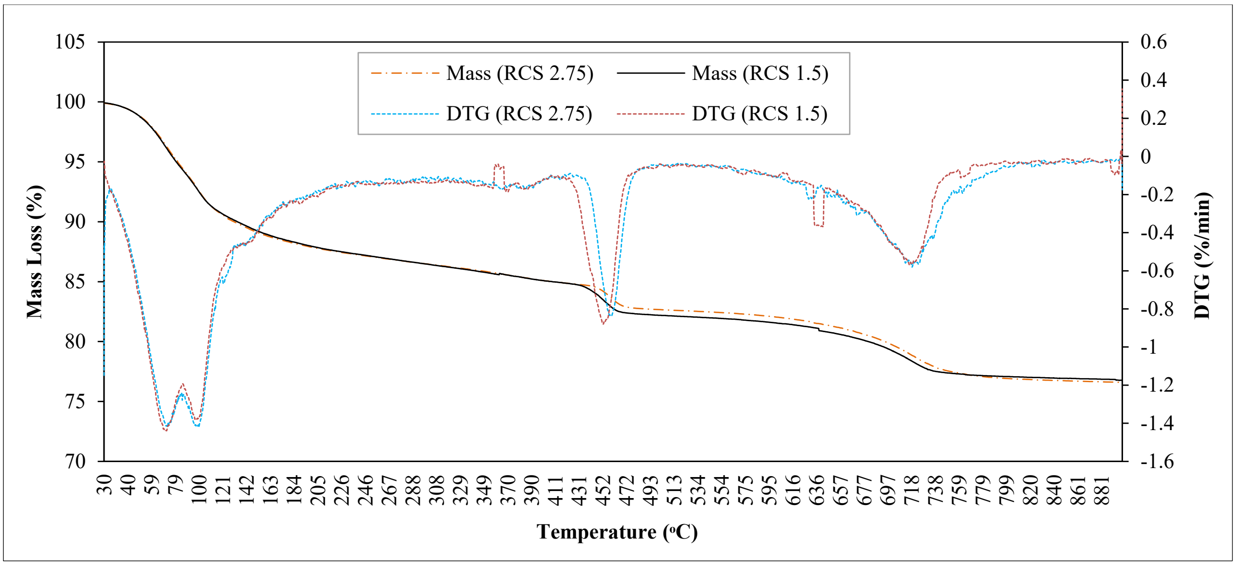
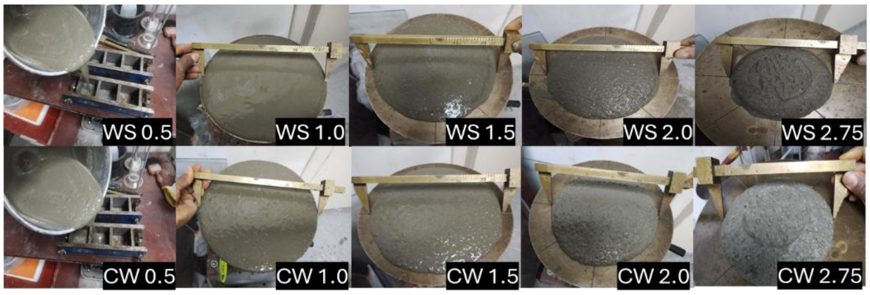


Figure 10. TGA/DTG of RCS mortar

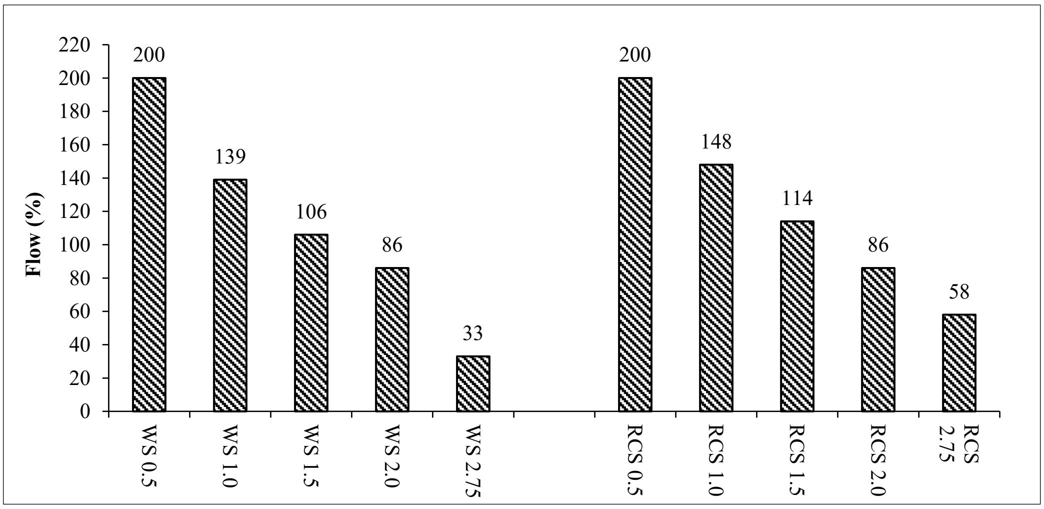
The $Ca(OH)_2$ decomposition peak between 400 and 500°C shows minor variation, indicating that both mixes have undergone similar degrees of hydration [53]. The concordance between the FTIR and TGA profiles of RCS 1.5 and RCS 2.75 is expected, as these analyses primarily focus on chemical composition and thermal decomposition, which are not significantly affected by changes in the sand-to-cement ratio. Therefore, the observed differences in compressive strength are attributed to microstructural factors such as density, porosity, and particle packing, which are not directly captured by FTIR and TGA results.

3.2. Workability

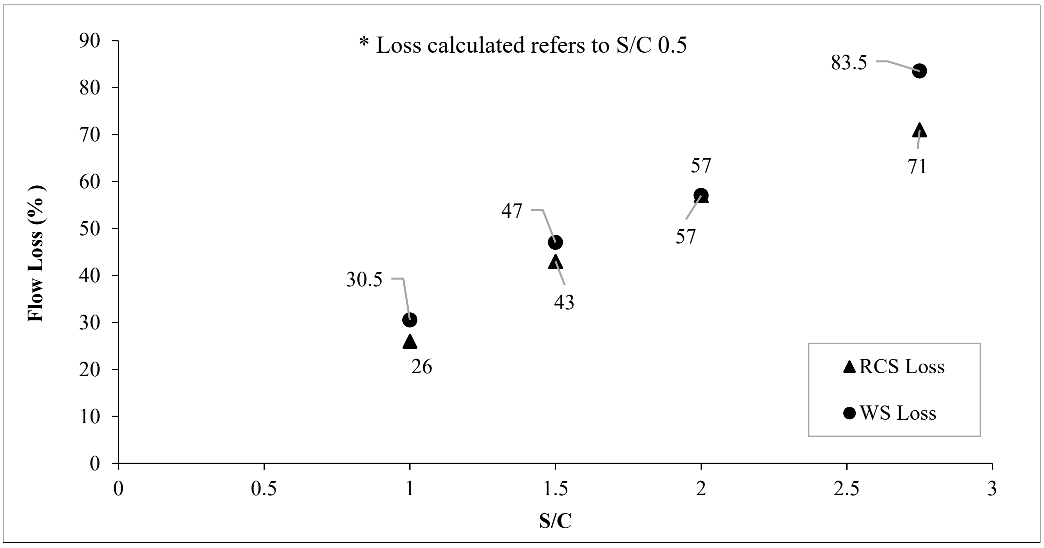
The flow table tests for mortar mixes (Figures 11-a and 11-b) illustrate the flow shape and workability results based on sand type and sand-to-cement (S/C) ratio, respectively. The target flow set point for mortar mixes was 110 ± 5%, as specified by ASTM C109. At higher S/C ratios, particularly WS 2.75, the flow values for washed sand (WS) significantly decreased to 33%, indicating very low workability. Conversely, at the lower ratio (WS 0.5), flow values were extremely high, producing a fluid-like consistency. This sharp decrease in flow at higher sand concentrations reflects how increased sand content reduces mortar workability and consistency.



(a)



(b)



(c)

Figure 11. Flow table (a) shape, (b) results, (c) percentage loss

At an S/C ratio of 1.0, WS achieved a flow of 139%, exceeding the target range, while WS 1.5 produced a flow of 106%, falling within the desired range and indicating optimal workability. In contrast, RCS 0.5 exhibited highly fluid behavior, whereas RCS 2.75 showed a reduced flow of 58%, indicating decreased workability at higher sand content.

Although the higher absorption rate of RCS does not negatively affect workability, at higher S/C ratios, RCS exhibits greater flowability due to its particle shape and texture. Conversely, WS, with its lower absorption rate, displayed lower flow values at S/C ratios of 1.0, 1.5, and 2.75, and similar values at S/C 2.0. This demonstrates the significant influence of absorption and mineral composition on mortar workability. Both WS 1.5 and RCS 1.5 correspond to the optimum flow range of 110 ± 5%, making them suitable for practical applications.

These results indicate that achieving satisfactory workability and performance from mortar mixtures depends on considering absorption properties alongside particle morphology. As reported in previous research by Zhang et al. [2], these findings follow a similar trend observed with natural sand. The results demonstrated that flow spread significantly increased as the sand-to-cement (S/C) ratio decreased. When the S/C ratio increased, additional water was required to maintain consistent flowability. At a fixed water-to-cement (W/C) ratio of 0.40, the mortar with an S/C ratio of 3.2 exhibited no measurable flow, while the mix with an S/C ratio of 2.4 achieved a flow spread of 53.5 mm, reflecting a spread improvement of 53.5 mm. When the W/C ratio was raised to 0.60, flow spread improved for both mixes: the mortar with an S/C ratio of 3.2 reached 82.5 mm, and that with an S/C ratio of 2.4 reached 200 mm, resulting in a spread increase of 117.5 mm.

Figure 11-c illustrates the flow loss percentage for both WS and RCS mixtures, calculated relative to the initial flow value at an S/C ratio of 0.5. The flow loss trends indicate that WS mixtures experience a more gradual reduction in flowability, with a maximum loss of 71% at an S/C ratio of 2.75. Conversely, RCS exhibits a more substantial decrease in flow, especially at higher S/C ratios, where the loss reaches a significant 83.5%. At an S/C ratio of 1.0, WS shows a flow loss of approximately 30.5%, while RCS records a slightly lower loss of 26%. As the S/C ratio increases to 1.5, flow loss intensifies for both materials, with WS losing 47% and RCS losing 43% of their initial flowability. The difference between the two materials becomes less pronounced at an S/C ratio of 2.0, with both exhibiting nearly identical losses of 57%. The most notable contrast occurs at the maximum S/C ratio of 2.75, where WS and RCS display flow losses of 71% and 83.5%, respectively. This marked difference underscores the critical challenge of using RCS in high-sand-content mixtures, as the internal resistance between angular and rough particles leads to severe flowability loss.

3.3. Compressive Strength

Figure 12 shows the variation in compressive strength of mortar samples prepared with Washed Sand (WS) and Recycled Concrete Sand (RCS) at different sand-to-cement (S/C) ratios. The highest compressive strength was achieved at the lowest S/C ratio for WS 0.5, reaching 36.7 MPa at 7 days and 51.3 MPa at 28 days. However, as sand content increased, strength gradually decreased, with WS 2.75 exhibiting a minimum strength of 48.3 MPa at 28 days. This trend indicates that increasing sand content weakens the mortar matrix due to dilution of the cementitious phase [50].

Similarly, RCS mortars showed lower compressive strength than WS mortars at all S/C ratios. For example, the 28-day strength for RCS 0.5 was 40.3 MPa, significantly lower than WS 0.5 (51.3 MPa). As the S/C ratio increased, the decline in strength became more pronounced, with RCS 2.75 recording the lowest strength of 29.2 MPa at 28 days, the lowest among all mixes tested.

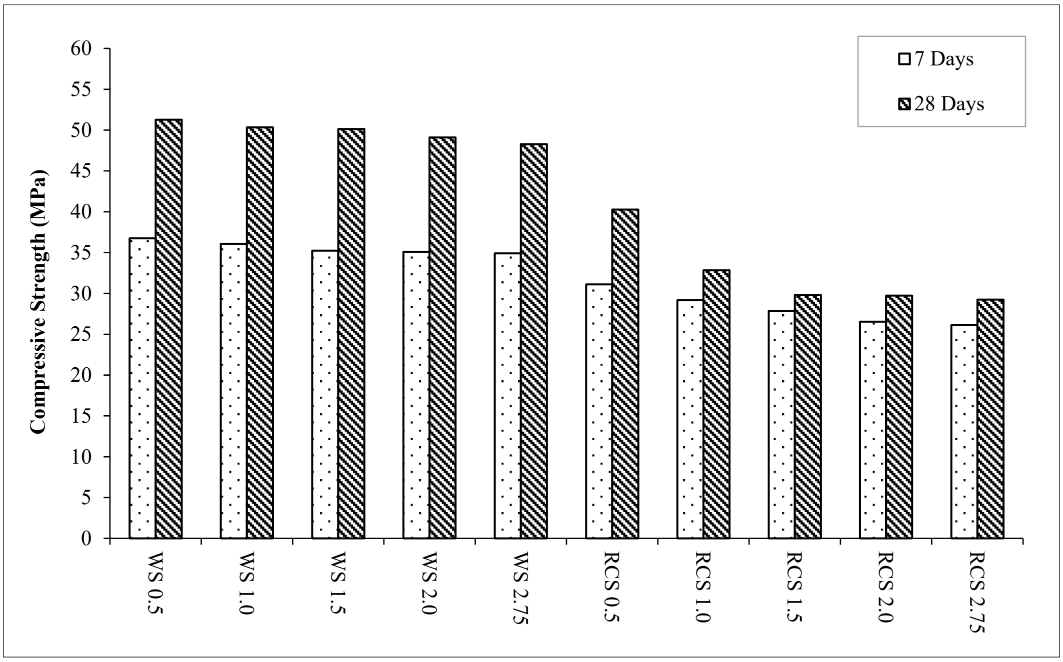


Figure 12. Compressive strength results of mortar samples

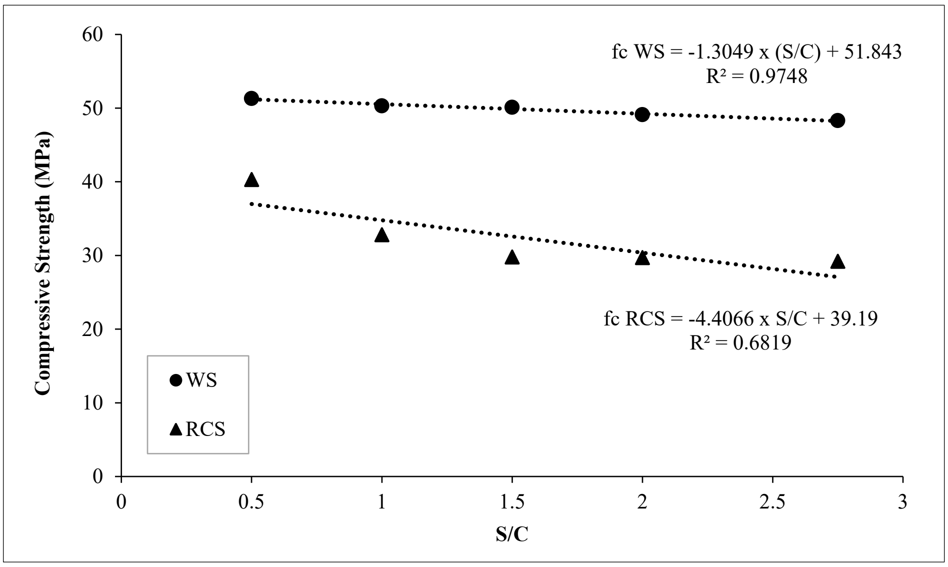
The lower strength of RCS mortars can be attributed to their higher porosity, angular particle shape, and reduced cementitious efficiency, which negatively affect particle packing and bond formation in the mortar [8, 12]. Mortars with S/C ratio 1.5 (both RCS 1.5 and WS 1.5) were selected based on optimal workability (110 ± 5% flow value) and compared: WS 1.5 recorded a compressive strength of 50.1 MPa at 28 days, while RCS 1.5 showed the lowest strength at 29.8 MPa. This difference is explained by the smoother texture of WS particles, which promotes denser packing and stronger interparticle bonds, whereas residual cementitious components in RCS increase porosity and reduce strength [44, 45].

The compressive strength results RCS 1.5 and other mortar mixes (RCS 2.0 and RCS 2.75) comply with specifications for Masonry Cement Types (N, S, M) outlined in ASTM C150 (Portland Cement), ASTM C1329 (Mortar Cement), ASTM C91 (Masonry Cement), and ASTM C270 (Mortar for Unit Masonry). This compliance indicates that mortars incorporating RCS can serve as suitable alternatives in various construction of non-structural applications, especially when workability challenges are addressed by adding superplasticizers to improve flow.

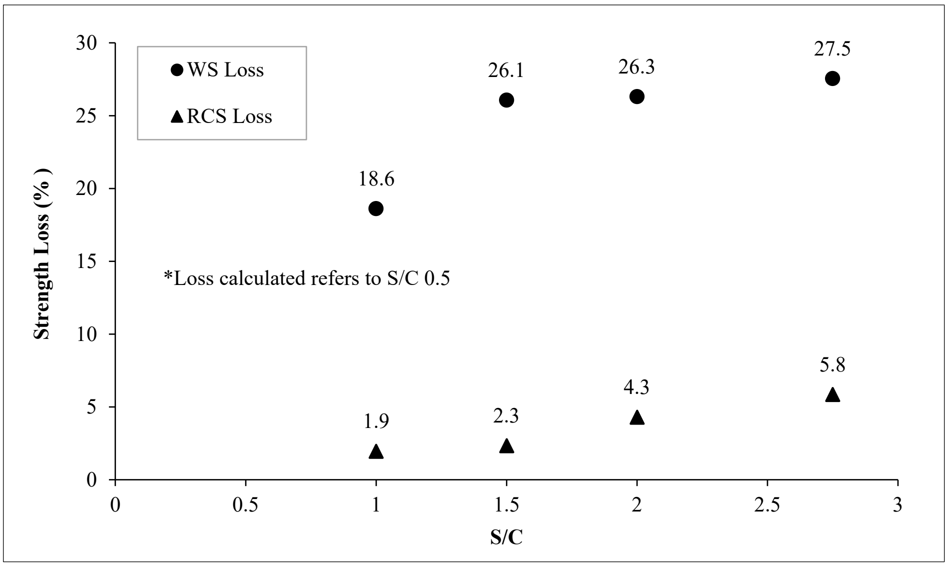
As reported in previous research by Zhang et al. [2], these findings follow a similar trend observed with natural sand. At a constant sand-to-cement (S/C) ratio, the compressive strength of the mortar was found to decrease as the water-to-cement (W/C) ratio increased. When comparing strength curves across different S/C ratios, the results showed that at a high W/C ratio of 0.60, the compressive strengths of all mixes were relatively similar. This indicated that the S/C ratio had minimal influence on strength under high water conditions. However, when the W/C ratio was below 0.50, increasing the S/C ratio led to a significant reduction in strength. These observations suggest that the impact of the S/C ratio on mortar strength became more pronounced at lower W/C ratios. Since cement served as the sole binding agent in the mixes, a higher S/C ratio resulted in a lower cement content per unit volume, reducing the amount of binder available. Additionally, increasing the S/C ratio introduced more voids between sand particles, further contributing to the reduction in strength.

The results, presented in Figure 13-a, reveal a consistent decline in compressive strength as the S/C ratio increases for both WS and RCS. The compressive strength of WS exhibited a gradual decrease, following a linear regression Equation (Equation 1):

$$fc\,(WS) = -1.3049 \times (S/C) + 51.843 \tag{1}$$



(a)



(b)

Figure 13. Compressive strength performance (a) results, (b) percentage loss

In contrast, the compressive strength of RCS decreased more steeply, as indicated by the following linear regression Equation (Equation 2):

$$fc\ (RCS) = -4.4066 \times (S/C) + 39.19 \qquad (2)$$

The higher slope value for RCS indicates that strength degradation is significantly more pronounced compared to WS. At a low S/C ratio of 0.5, the compressive strength of WS reached approximately 50 MPa, while RCS exhibited a reduced strength of around 40 MPa, representing a 21.4% decrease. As the S/C ratio increased to 1.0, the strength gap widened further, with WS maintaining around 49 MPa and RCS dropping to 33 MPa, resulting in a 34.8% loss. This trend continued at higher S/C ratios, where the strength reduction in RCS peaked at approximately 40.5% for an S/C ratio of 1.5, then stabilized at around 39.5% for ratios between 2.0 and 2.75. The R^2 value for WS (0.9748) indicates a very strong linear correlation between compressive strength and the sand-to-cement ratio, suggesting that WS mortars behave in a consistent and predictable manner. In contrast, the lower R^2 value for RCS (0.6819) suggests that the relationship is weaker and more scattered, likely due to the inherent variability in recycled concrete sand properties, such as higher porosity, residual cementitious material, and inconsistent particle morphology. These factors introduce variability in performance, reducing the predictability of compressive strength trends with increasing S/C ratios.

The strength loss percentage between WS and RCS was calculated with reference to the initial compressive strength at an S/C ratio of 0.5, as shown in Figure 13-b. Strength loss for WS remained relatively low, increasing from 1.9% at an S/C ratio of 1.0 to 5.8% at 2.75. In contrast, RCS displayed significantly higher strength loss, starting at 18.6% for an S/C ratio of 1.0 and reaching 27.5% at 2.75. This substantial difference highlights the vulnerability of RCS to strength reduction when used in mixtures with elevated sand-to-cement ratios.

Table 4 presents the standard deviation values of compressive strength results for both 7-day and 28-day curing periods across various mortar mix designs. The results demonstrate that most mixes exhibited good repeatability and low variability, with nearly all standard deviations falling well below the acceptable threshold of 1.0 MPa as recommended by ASTM C109. In the WS series, the 7-day deviations were particularly low, ranging from 0.06 MPa (WS 0.5) to 0.35 MPa (WS 1.5), while 28-day values remained under 0.9 MPa, indicating consistent strength development over time. Similarly, the CW mixes showed acceptable variation, with notably low standard deviations for CW 0.5 and CW 2.75 at 28 days (0.06 MPa each). The highest variation was observed in CW 1.0 at 7 days (0.65 MPa) and CW 2.0 at 28 days (0.72 MPa), though still within reasonable limits.

Table 4. Average and Standard deviation of compressive strength results

Mix ID		Average 7 days (MPa)	Standard Deviation 7 days (MPa)	Average 28 days (MPa)	Standard Deviation 28 days (MPa)
WS	WS 0.5	36.7	0.06	51.3	0.75
	WS 1.0	36.1	0.15	50.3	0.35
	WS 1.5	35.2	0.35	50.1	0.21
	WS 2.0	35.1	0.1	49.1	0.26
	WS 2.75	34.9	0.1	48.3	0.9
CW	CW 0.5	31.1	0.17	40.3	0.06
	CW 1.0	29.2	0.65	32.8	0.55
	CW 1.5	27.9	0.06	29.8	0.4
	CW 2.0	26.5	0.46	29.7	0.72
	CW 2.75	26.1	0.2	29.7	0.06

3.4. Hardened Density

Figure 14 illustrates the hardened densities of mortar specimens made with washed sand (WS) and recycled concrete sand (RCS) across varying sand-to-cement (S/C) ratios, measured at both 7 and 28 days of curing. Across all mixtures, there was a consistent increase in hardened density from 7 to 28 days, attributed to ongoing hydration of cement particles, which resulted in additional formation of hydration products and a denser microstructure. This development confirms that extended curing enhances mortar compactness by filling capillary pores and refining the internal structure.

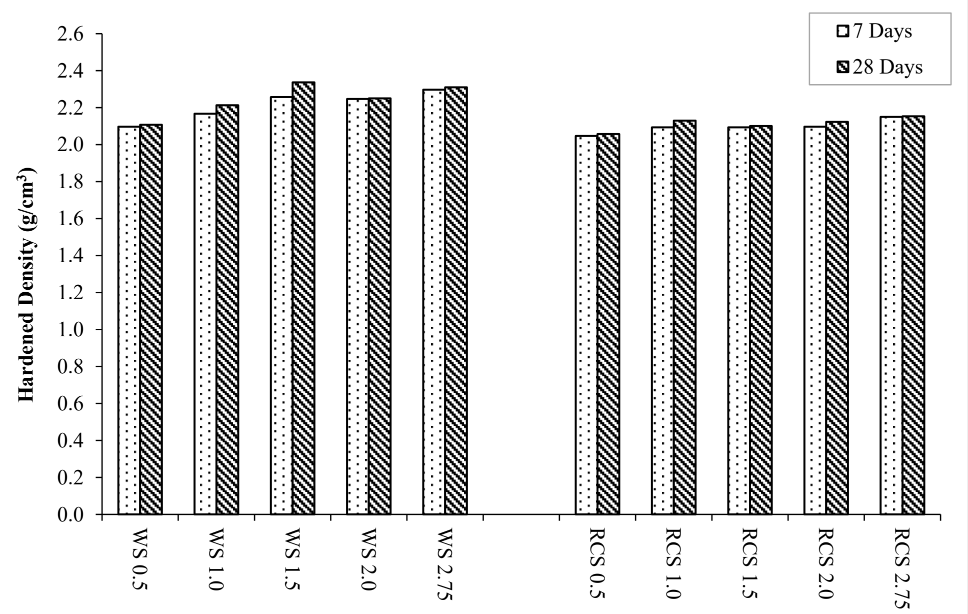


Figure 14. Hardened density results of mortar samples

A clear distinction is observed between the two sand types. WS-based mortars consistently exhibited higher hardened densities than those made with RCS, regardless of the S/C ratio or curing age. For example, the highest 28-day density among WS mortars was recorded at S/C 1.5 (2.337 g/cm³), compared to 2.153 g/cm³ for the RCS mix at S/C 2.75. The lower density values in RCS mortars are mainly due to the higher porosity of recycled aggregates, the irregular and angular particle shapes that reduce packing efficiency, and the presence of adhered old cement paste. These factors contribute to more voids and entrapped air in the mixture, reducing overall compactness. Additionally, the higher water absorption of RCS reduces the effective water available for cement hydration, which can also influence density development.

The influence of the S/C ratio followed a distinct trend for both sand types. At lower S/C ratios (0.5 to 1.5), increasing sand content generally improved the density due to better particle interlocking and more efficient void filling. However, beyond an S/C ratio of 1.5, the density either plateaued or slightly declined, likely because the increase in sand came at the expense of cement paste volume, which is essential for bonding and densification. This trend was more evident in WS mortars, where the 28-day density rose from 2.107 g/cm³ at S/C 0.5 to 2.337 g/cm³ at S/C 1.5, before slightly dropping to 2.31 g/cm³ at S/C 2.75. A similar, though less pronounced, pattern was observed for RCS mortars, with a steady but limited increase in density from 2.057 g/cm³ at S/C 0.5 to 2.153 g/cm³ at S/C 2.75.

The plot in Figure 15 shows the relationship between density and compressive strength for WS and RCS materials. WS exhibits higher density (2.2-2.3 g/cm³) and compressive strength (45-50 MPa) with a moderate correlation (R^2 = 0.5026), indicating relatively stable performance. In contrast, RCS shows lower density (2.1-2.2 g/cm³) and compressive strength (30-40 MPa) with a stronger correlation (R^2 = 0.6746), highlighting a significant drop in strength as density decreases.

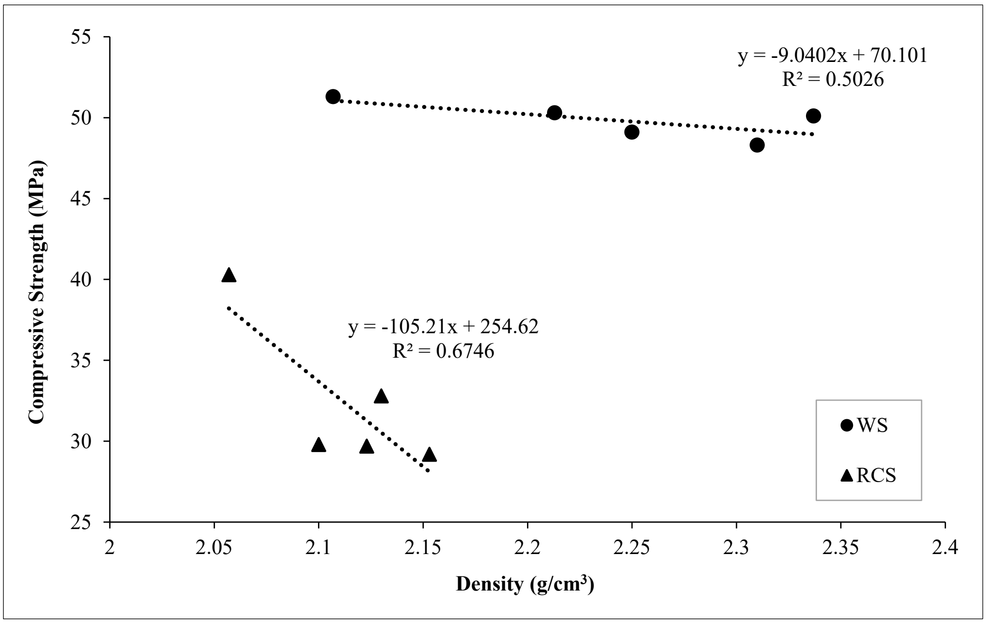


Figure 15. Relationship between density and compressive strength

3.5. Water Absorption

Figure 16 presents the 24-hour water absorption results for mortar specimens prepared with washed sand (WS) and 100% recycled concrete sand (RCS) at five different sand-to-cement (S/C) ratios: 0.5, 1.0, 1.5, 2.0, and 2.75. For the WS series, water absorption values increased progressively from 1.2% at WS 0.5 to 2.1% at WS 1.0, 3.2% at WS 1.5, 6.3% at WS 2.0, and peaked at 7.3% for WS 2.75. This upward trend indicates that increasing the S/C ratio reduces the paste content and cohesion within the mix, leading to a more porous microstructure that allows more water ingress [52, 2]. A similar but more pronounced trend was observed in the RCS mixes, starting from 5.0% at RCS 0.5, rising to 6.2% at RCS 1.0, 7.3% at RCS 1.5, 8.2% at RCS 2.0, and reaching the highest absorption of 9.5% at RCS 2.75.

These results confirm two critical patterns. First, water absorption consistently increases as the S/C ratio increases, for both sand types. The reduced cement content at higher S/C ratios limits the ability of the paste to fill voids and coat aggregate particles, resulting in more capillaries and interconnected pores. Second, RCS mortars exhibited substantially higher water absorption than WS mortars at every S/C ratio. At S/C 0.5, for example, RCS absorbed 5.0%, which is more than four times that of WS at 1.2%. This discrepancy is attributed to the intrinsic characteristics of recycled sand, including higher porosity, rougher surfaces, and the presence of residual adhered mortar, all of which increase the material's water-holding capacity.

Notably, the absorption difference between the two sands becomes more pronounced at higher S/C ratios. At S/C 2.0, WS recorded 6.3%, while RCS reached 8.2%; at S/C 2.75, WS was 7.3% compared to RCS at 9.5%. These findings underscore the influence of aggregate type and mix proportion on porosity-related behaviour. In practical terms, increased water absorption is associated with higher permeability and lower durability, making high S/C mixes especially those with RCS more vulnerable to environmental degradation.

Previous studies have confirmed that water absorption is a key durability indicator for mortar, and is strongly influenced by the porosity of the matrix. As reported by Mora-Ortiz et al. [54], water absorption increases as the water-to-cement (W/C) ratio and the proportion of recycled aggregates rise, due to the higher water demand and inherent porosity of recycled materials. The highest absorption values are observed in mixes with 100% RFA and no additives, indicating greater porosity.

Although WS mortars have a denser particle structure and thus a lower absorption coefficient, RCS mortars exhibit greater inherent porosity and a rougher texture. The addition of pozzolanic materials such as metakaolin, fly ash, and silica fume to RCS mortars can substantially improve properties like porosity and durability, these materials react with calcium hydroxide, a product of cement hydration, to form additional calcium silicate hydrate (C-S-H), which contributes to mortar strength [53].

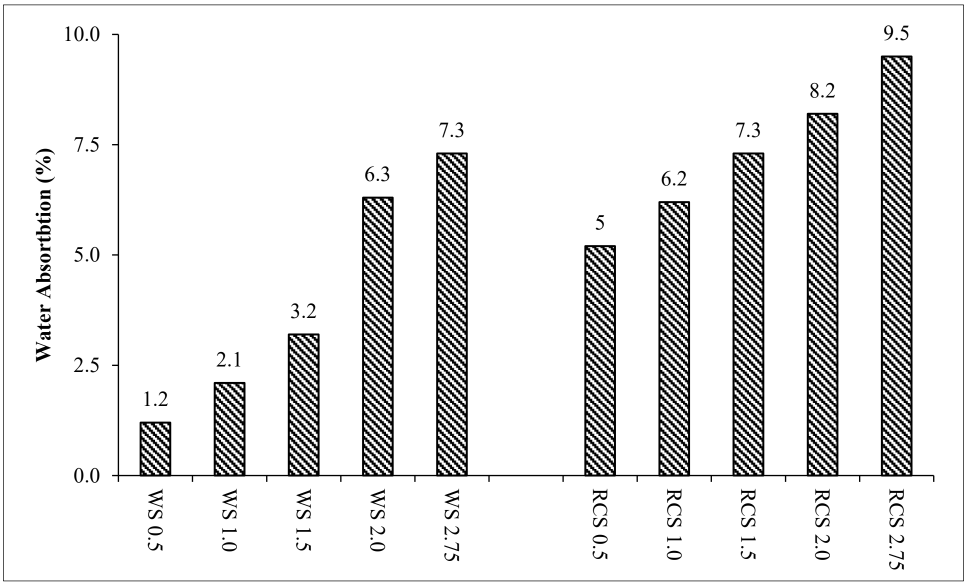


Figure 16. Water absorption results of mortar samples

3.6. Integrated Evaluation

The radar chart for washed sand (WS) mortars reveals distinct trends across different sand-to-cement (S/C) ratios. At an S/C ratio of 0.5, the mortar mix exhibited the highest flow value at 200%, the greatest compressive strength (51.3 MPa), and the lowest water absorption (1.2%). However, the density was also the lowest at 2.107 g/cm³, suggesting a less compact matrix due to excessive cement paste. As the S/C ratio increased to 1.0 and 1.5, the flow reduced to 139% and 106%, respectively, but the density increased significantly to 2.213 g/cm³ and 2.337 g/cm³, indicating a more optimal packing of sand particles. Although compressive strength slightly decreased, it remained high at 50.3 MPa and 50.1 MPa, and water absorption stayed at manageable levels (2.1% and 3.2%).

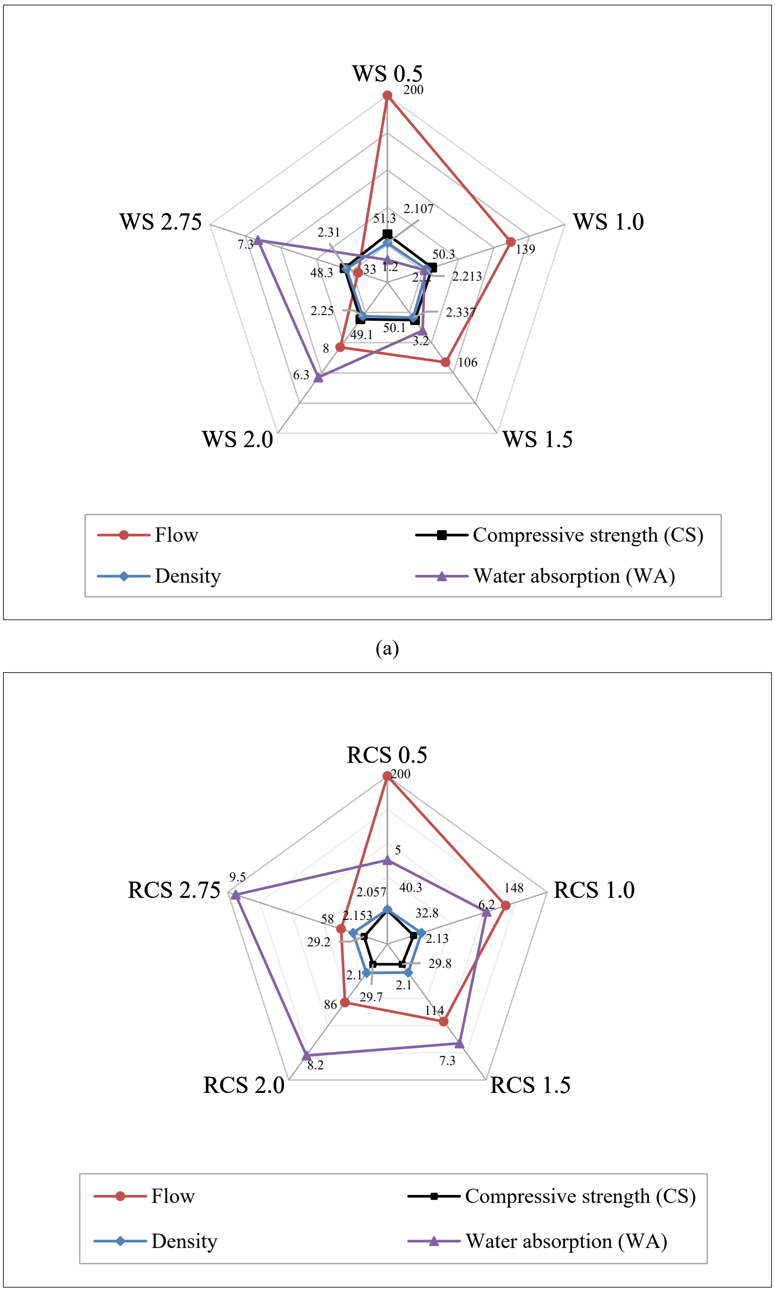
At higher S/C ratios (2.0 and 2.75), flow dropped sharply to 48.3% and 33%, respectively, indicating poor workability. While density continued to rise to 2.31 g/cm³ at WS 2.75, compressive strength declined to 49.1 MPa and 48.3 MPa, and water absorption spiked to 6.3% and 7.3%, highlighting the formation of voids due to insufficient binder. These results confirm that WS 1.5 achieves the most balanced performance across all parameters, offering ideal flow, high strength, excellent density, and acceptable water absorption.

The radar chart for 100% recycled concrete sand (RCS) mortars also shows significant variations with changing S/C ratios. At S/C 0.5, the flow was exceptionally high at 200%, and the compressive strength peaked at 40.3 MPa, but density was lowest at 2.057 g/cm³, and water absorption was moderately high at 5.0%. As the S/C ratio increased to 1.0 and 1.5, the flow decreased to 148% and 114%, respectively, while the density slightly increased to 2.13 g/cm³ and 2.10 g/cm³. Compressive strength dropped to 32.8 MPa and 29.8 MPa, respectively, and water absorption increased to 6.2% and 7.3%, showing increased porosity.

At higher S/C ratios, RCS 2.0 and 2.75 showed poor performance across most parameters. Flow fell to 86% and 58%, compressive strength decreased to 29.7 MPa and 29.2 MPa, and water absorption rose sharply to 8.2% and 9.5%, indicating weak bonding and excessive voids. While the density of RCS 2.75 reached 2.153 g/cm³, this increase did not translate into better strength or durability. Overall, RCS 1.5 was the most balanced among the recycled mixes, delivering relatively acceptable strength, moderate flow, and manageable absorption.

When comparing WS and RCS mortars, it is evident that WS mixtures consistently outperformed RCS in terms of compressive strength, workability, and durability. Although both materials showed an increase in density up to a certain

S/C ratio, RCS exhibited higher water absorption across the board due to its porous and angular nature. Importantly, the radar charts emphasize that S/C ratio 1.5 is the optimal point for both WS and RCS mortars, offering the best compromise between strength, flow, density, and water resistance. These findings reinforce the need for careful S/C ratio selection, especially when utilizing recycled materials, to ensure viable and sustainable mortar performance in practical construction applications.



(a)

(b)

Figure 17. Spider graph summarizing the test results (a) WS and (b) RCS

4. Conclusion

This study investigated the use of 100% recycled concrete sand (RCS) as a sustainable replacement for natural sand in cement mortar, with a particular focus on the effect of varying sand-to-cement (S/C) ratios while maintaining a fixed water-to-cement (w/c) ratio of 0.48. The results clearly indicated that increasing the S/C ratio led to a reduction in workability, compressive strength, and density, while water absorption increased. These changes are primarily attributed to the porous structure of RCS and the reduction in available cement paste to adequately bind the aggregate. The highest compressive strength was achieved at an S/C ratio of 0.5, while the most balanced performance in terms of strength and workability was observed at an S/C ratio of 1.5. Microstructural analysis supported these findings by revealing the presence of un-hydrated cementitious phases and residual calcium hydroxide within the RCS, which contributed to secondary hydration and slightly enhanced durability. Although the overall performance of RCS mortars was lower than those made with natural sand, the mixes still satisfied the essential requirements for non-structural applications such as plastering, rendering, and blockwork. Importantly, this study contributes to sustainable construction practices by demonstrating that optimized use of RCS can reduce the demand for natural sand, minimize construction and demolition waste, and promote circular economy principles. Furthermore, it fills a notable gap in current literature by systematically analyzing the effect of S/C ratio on mortars with 100% recycled concrete sand. These findings provide practical guidance for the development of environmentally responsible mortar formulations suitable for widespread application in the construction industry.

5. Declarations

5.1. Author Contributions

Conceptualization, M.R.I.; methodology, H.K.; validation, M.R.I.; formal analysis, M.R.I. and H.K.; writing—original draft preparation, M.R.I. and H.K.; writing—review and editing, M.R.I. and H.K.; visualization, H.K.; supervision, M.R.I.; project administration H.K.; funding acquisition, M.R.I. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

5.3. Funding

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5.4. Acknowledgements

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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